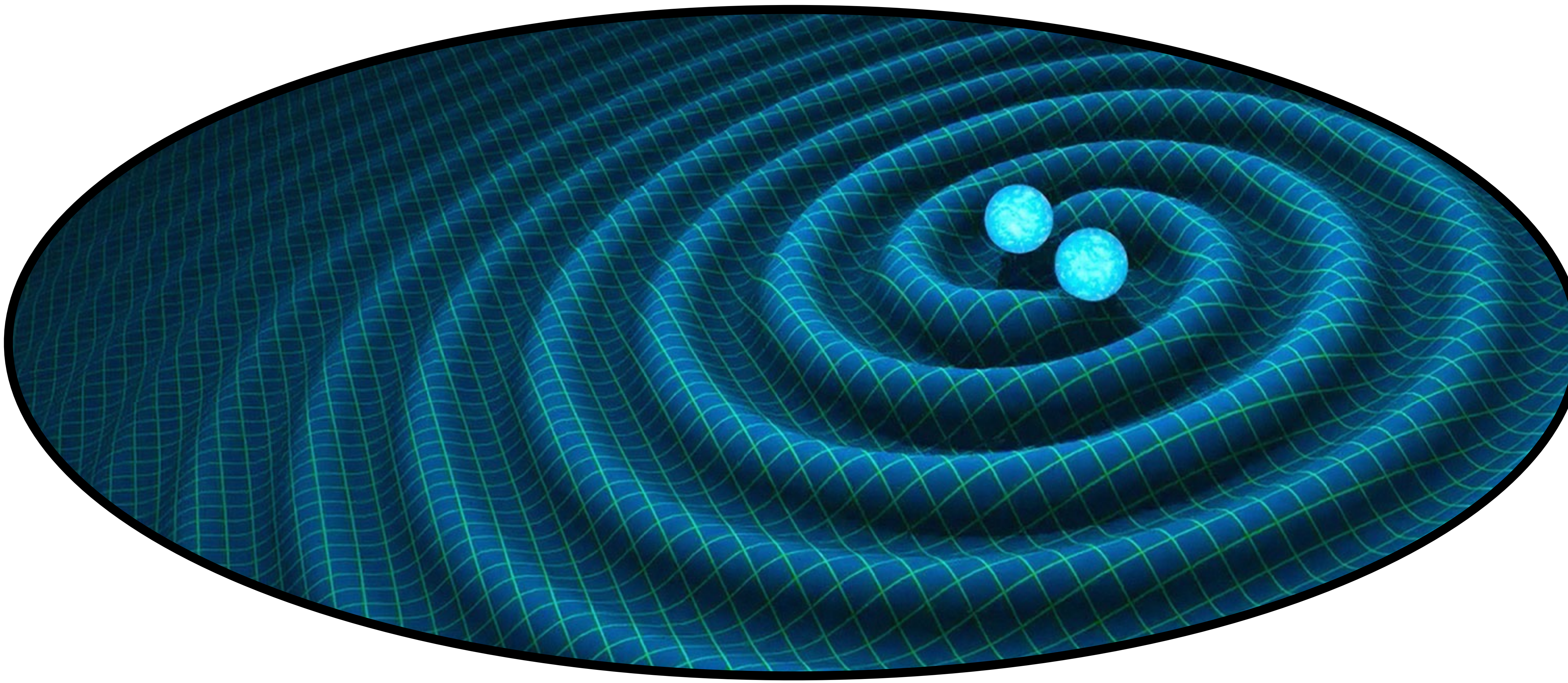
White Dwarf Mergers as Multi-Messenger Sources:

An overview of sources in galactic fields and dense star clusters



Kyle Kremer

Caltech & Carnegie Observatories

White Dwarf Mergers as Multi-Messenger Sources:

An overview of sources in galactic fields and dense star clusters

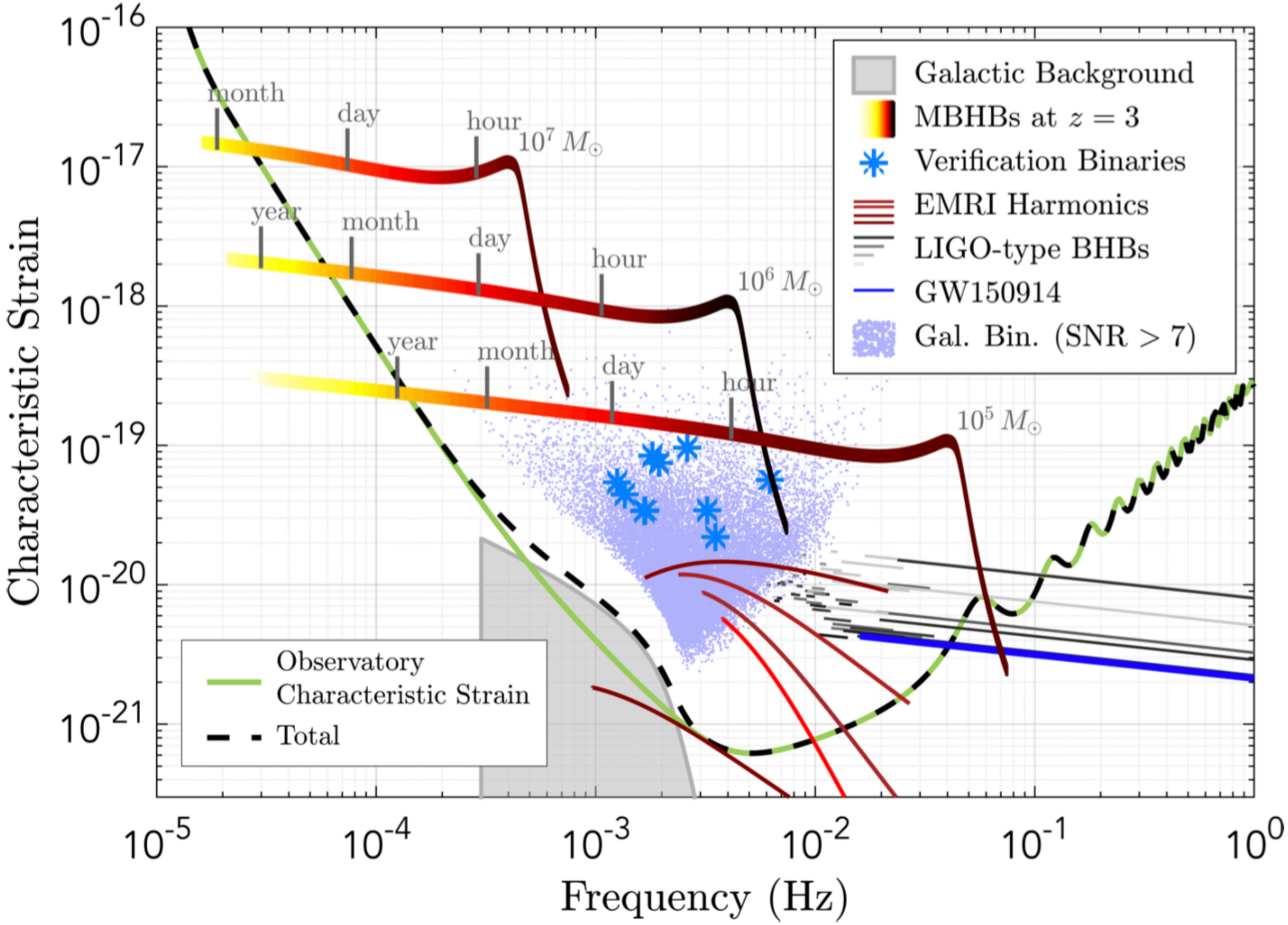
1. **Thousands of inspiraling Galactic white dwarf binaries will be resolvable as gravitational wave sources by LISA**

2. **White dwarf mergers may lead to a diverse range of outcomes**
   - Type Ia/Iax/.Ia SNe, "Ca-strong" transients, others?
     (Explosive WD transient session; K. Maguire, B. Rose, A. Polin)
   - Many likely collapse into neutron stars

3. **White dwarf mergers in dense star clusters**
   - Young radio pulsars observed
   - Recent *fast radio burst* in M81 globular cluster — a young magnetic neutron star born from white dwarf merger?

Kyle Kremer
Caltech & Carnegie Observatories

LISA: A millihertz gravitational wave observatory



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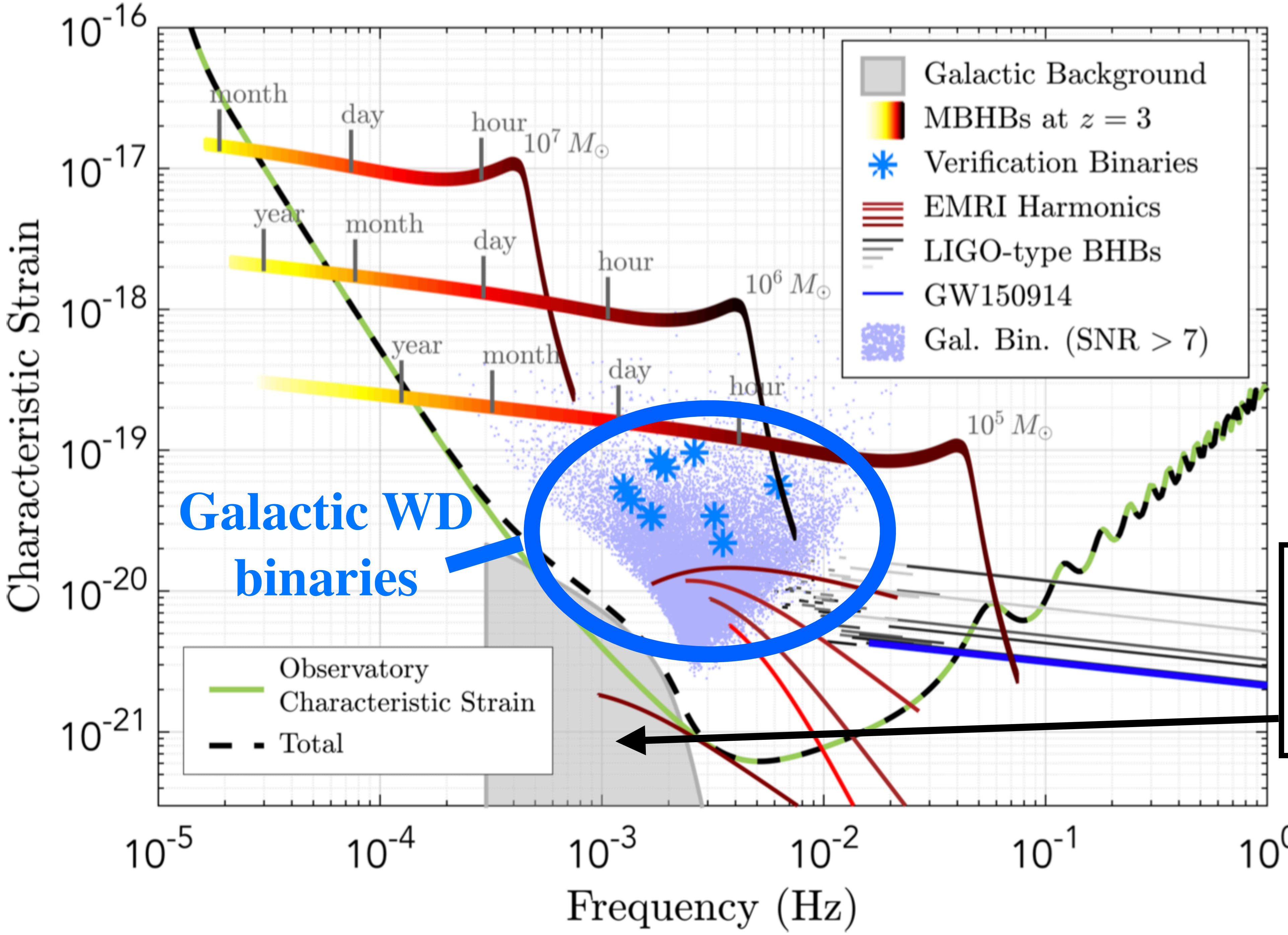


Unresolvable sources can constrain Galactic structure
(e.g., Benacquista & Holley-Bockelmann 2006, Korol+2019, Breivik+2020)

- Total white dwarf binaries in Milky Way: ~ 5 x 10^8
- Total with $f_{GW} > 10^{-4}$ Hz: ~ 6 x 10^7
- Total individually resolvable: ~ 10^3 - 10^4

e.g., Nelemans+2001, Ruiter+2010, Nissanke+2012, Lamberts+2019, Breivik+2020

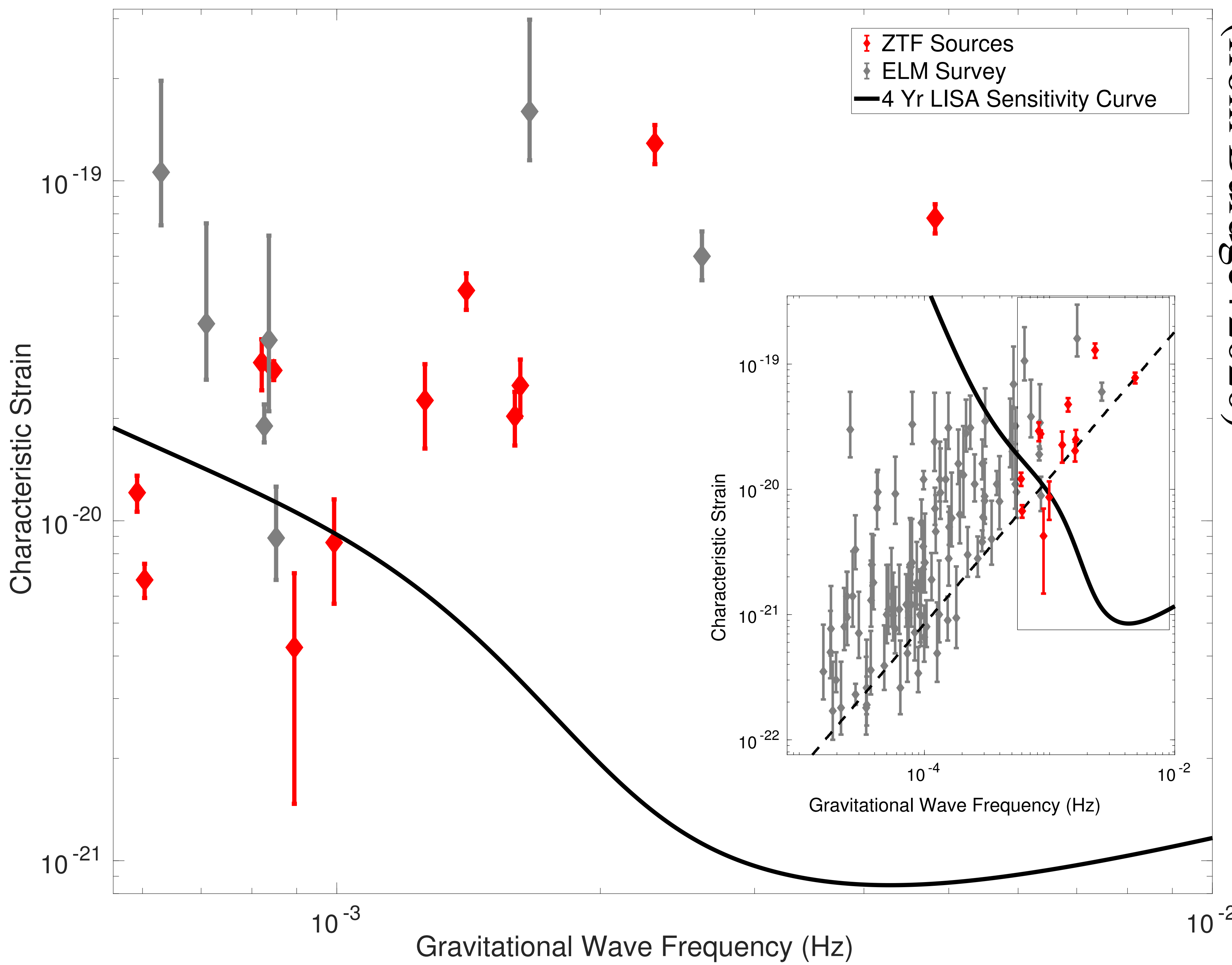
Growing catalog of LISA verification binaries

Zwicky Transient Facility (ZTF) survey *(~20 sources)*

(Burdge+2019a,2019b, 2020, Coughlin+2020, van Roestel+2022)

Extremely Low Mass (ELM) white dwarf survey *(~100 sources)*

(Brown+2010, 2012, 2013, 2020, Kilic+2011, 2012, 2014, Gianninas+2015)



(from Burdge+2020)

Session on non-terminal sources:
S. Scaringi, K. Burdge, R. Martinez-Galarza

Outcomes of White Dwarf Mass Transfer

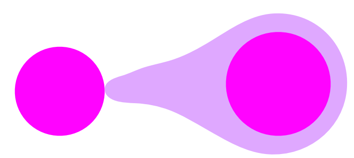
$$\dot{f} = \dot{f}_{\mathrm{GR}} + \dot{f}_{\substack{\text{mass}\\\text{transfer}}} + \dot{f}_{\mathrm{tides}}$$

Inspiral

Optical
(e.g., Burdge+2020)

Gravitational waves (LISA)
(e.g., Amaro-Seoane+2020)

Lower-mass white dwarf fills Roche lobe



Stable mass transfer? Merger?

Outcomes of White Dwarf Mass Transfer

$$\dot{f} = \dot{f}_{\mathrm{GR}} + \dot{f}_{\substack{\text{mass} \\ \text{transfer}}} + \dot{f}_{\text{tides}}$$

Stable mass transfer:

- Long-lived accreting binaries— AM CVn?

(e.g., Smak 1967, Paczyński 1967, Nather+1981, Tutukov & Yungleson 1996, Nelemans+2001, Marsh+2004, Gokhale+2007, Dan+2012, Kremer+2015)

- “Outspiralling” LISA sources?

(e.g., Kremer+2017, Breivik+2018, Tauris+2018)

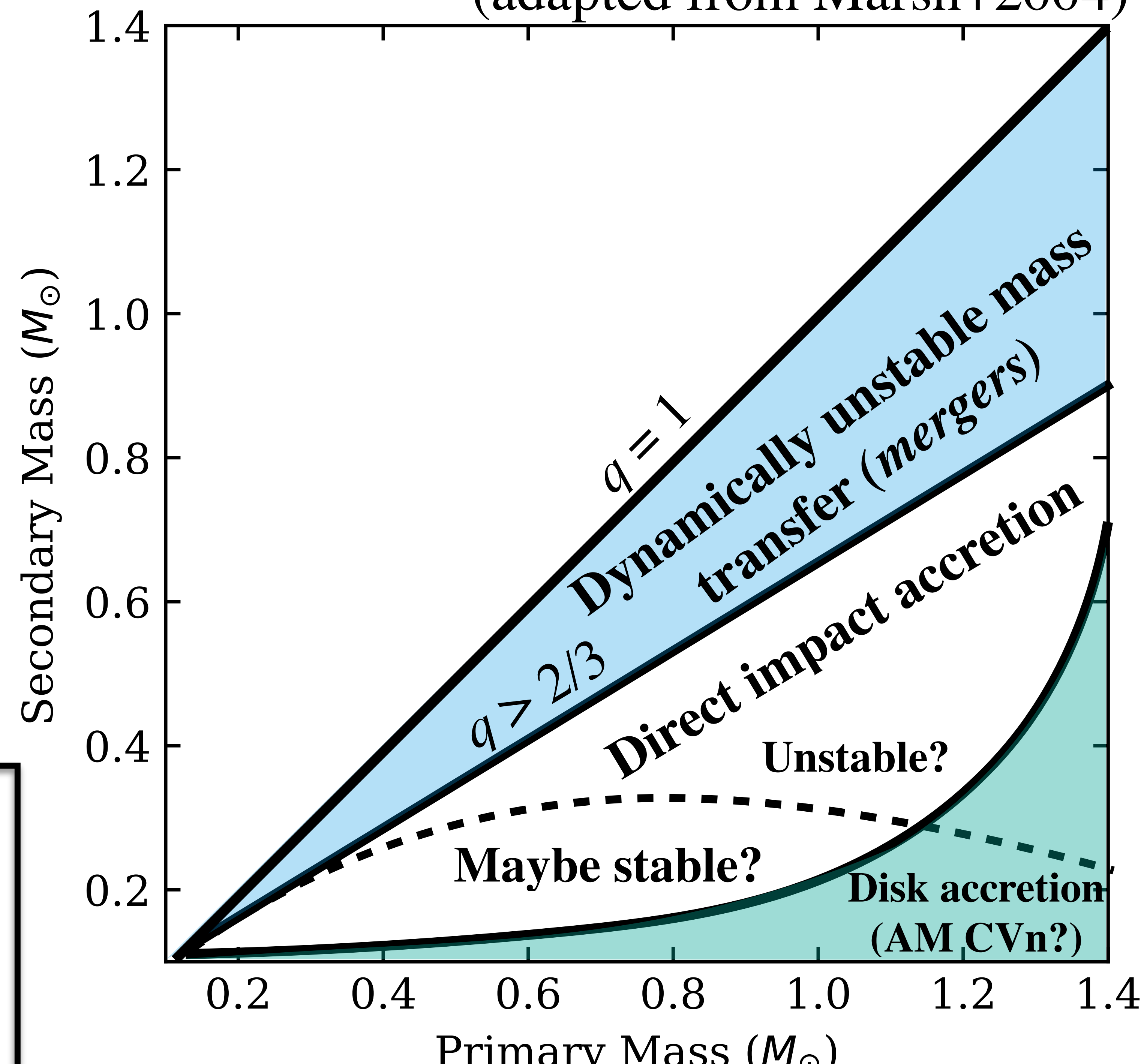
- Caveat? — *All* binaries may merge due to nova outbursts

(e.g., Shen 2015)

Unstable mass transfer:

- Mergers

(adapted from Marsh+2004)



Phases of Massive White Dwarf Mergers

Binary Inspiral	Dynamical (tidal disruption)	Viscous	Thermal	Final Remnant
$t \sim$ Myr	$t \sim 10^2$-10^3 s	$t \sim 10^4$-10^8 s	$t \sim 10^4$ yr	

Phases of Massive White Dwarf Mergers

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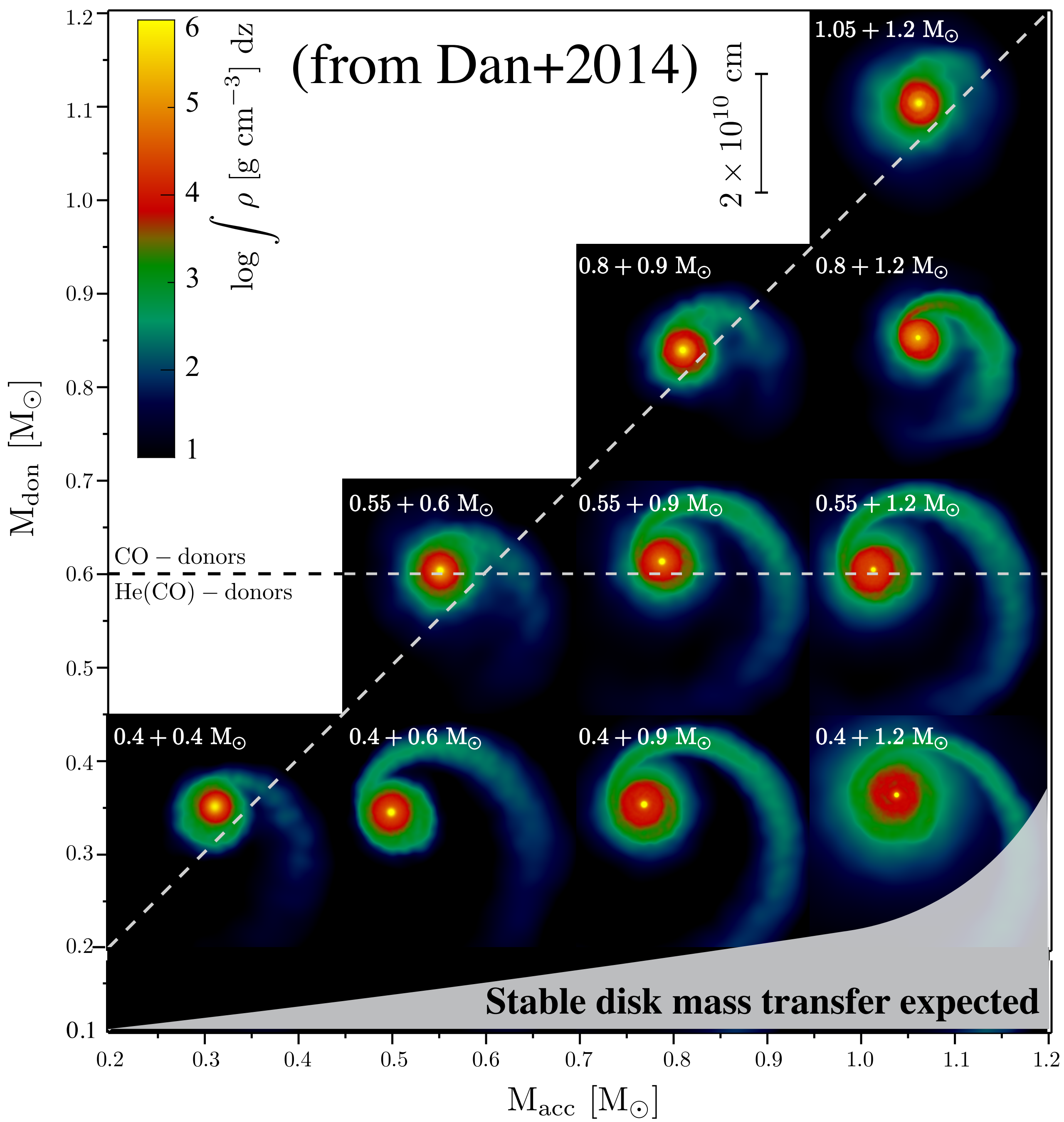
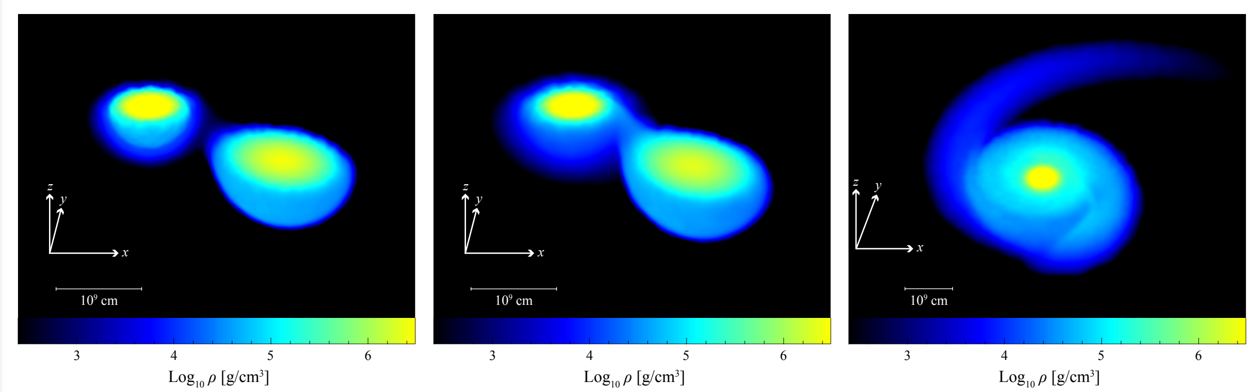
Mass ratio determines disruption dynamics



General outcome: Lower-mass WD is tidally disrupted and forms quasi-Keplerian disk around massive WD



For $q \sim 1$ and $M_{\mathrm{tot}} > 2.1 M_\odot$, temperatures may be hot enough to promptly ignite Carbon

→ super-Chandra Type Ia?

(e.g., SNLS-03D3bb; Howell+2006)

Hydrodynamic simulations: e.g., Benz+1990, Rasio & Shapiro 1995, Guerrero+2004, Yoon+2007, Lorén-Aguilar+2009, Pakmor+2010, Dan+2011, García-Berro+2012, Dan+2014

Phases of Massive White Dwarf Mergers

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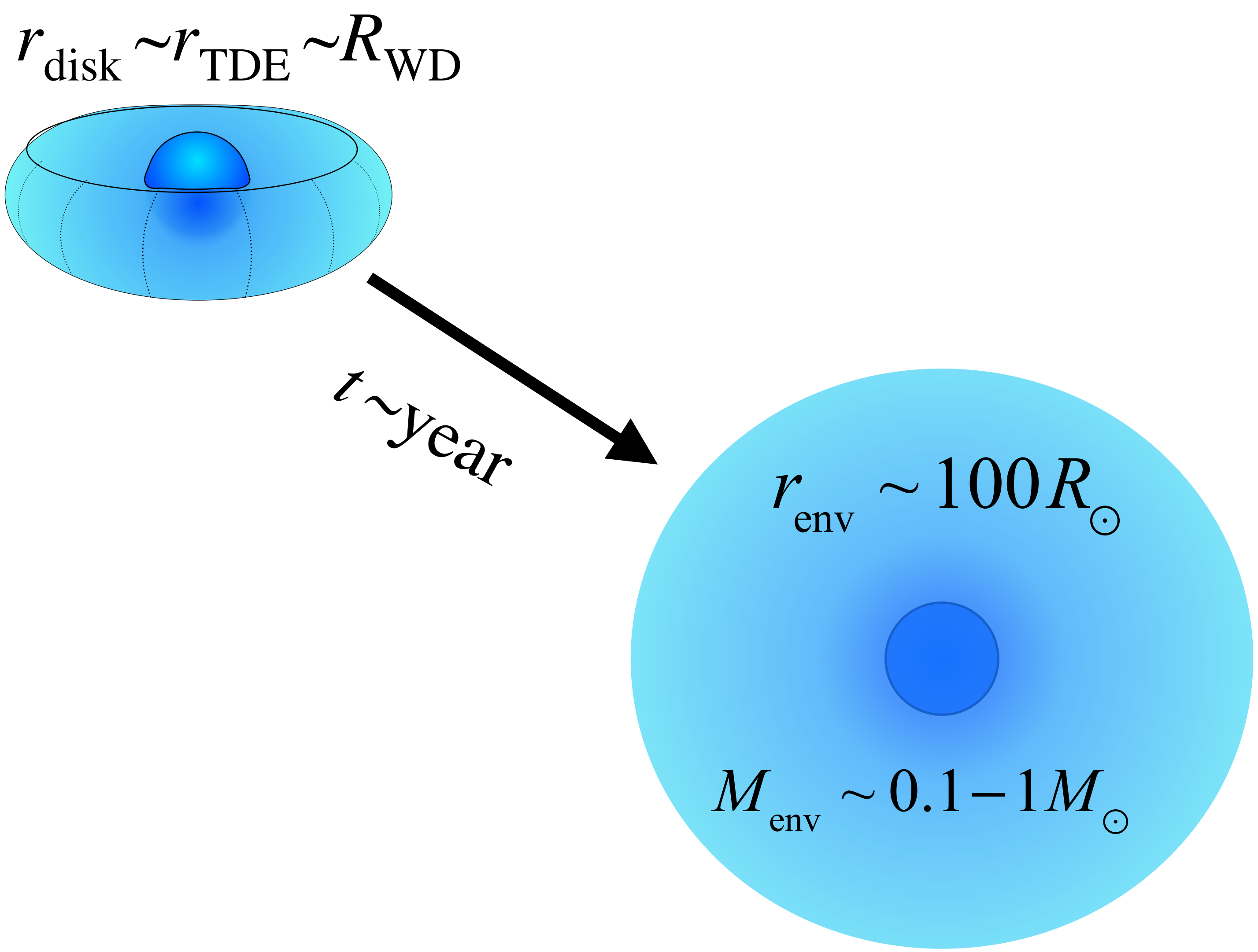
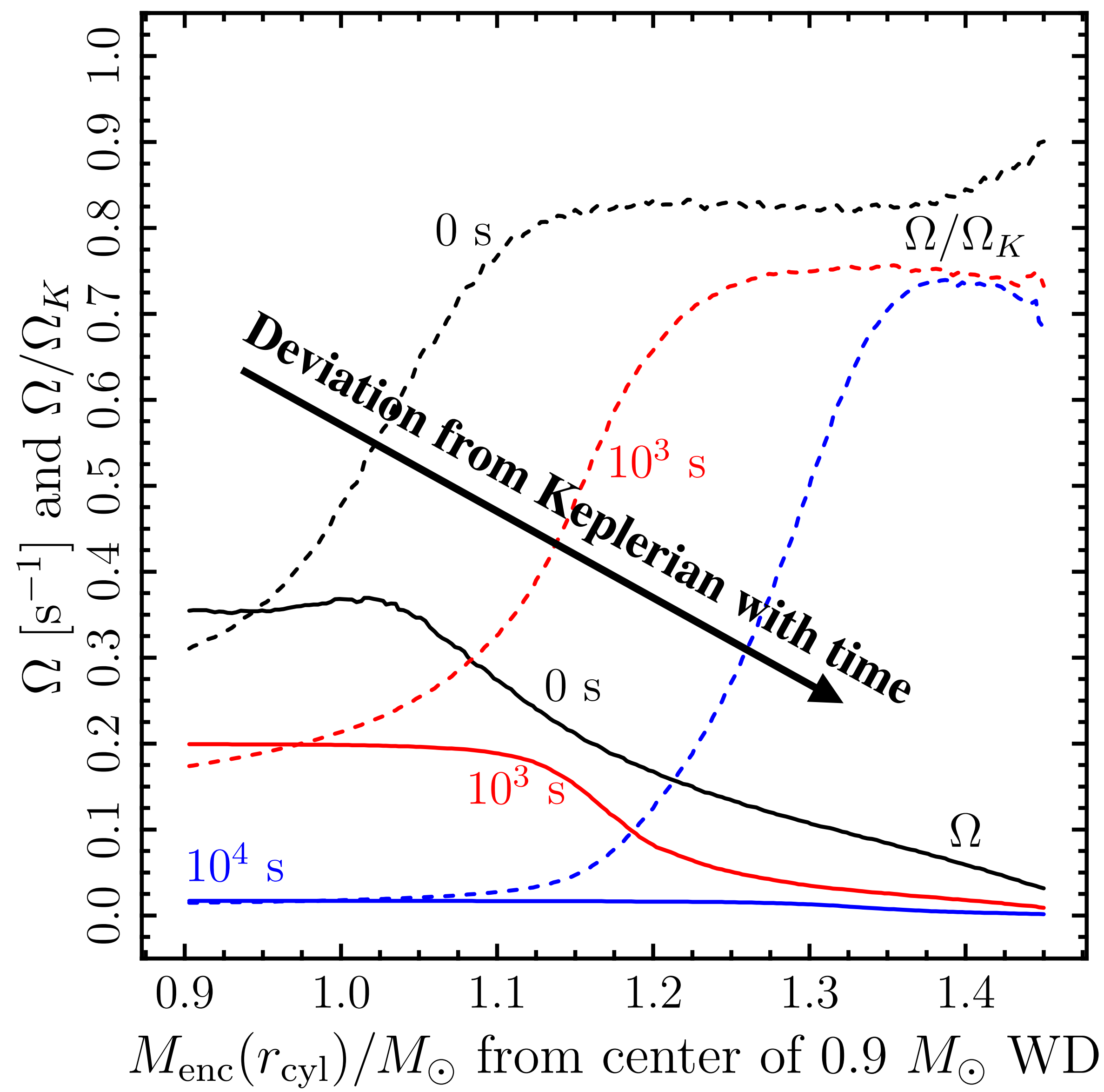
$t \sim$ Myr	$t \sim 10^2$-10^3 s	$t \sim 10^4$-10^8 s	$t \sim 10^4$ yr	

General outcome: Viscous heating in Keplerian disk leads to expansion and formation of *spherical envelope*



from Shen+2012



See also MHD simulations of Schwab+2012

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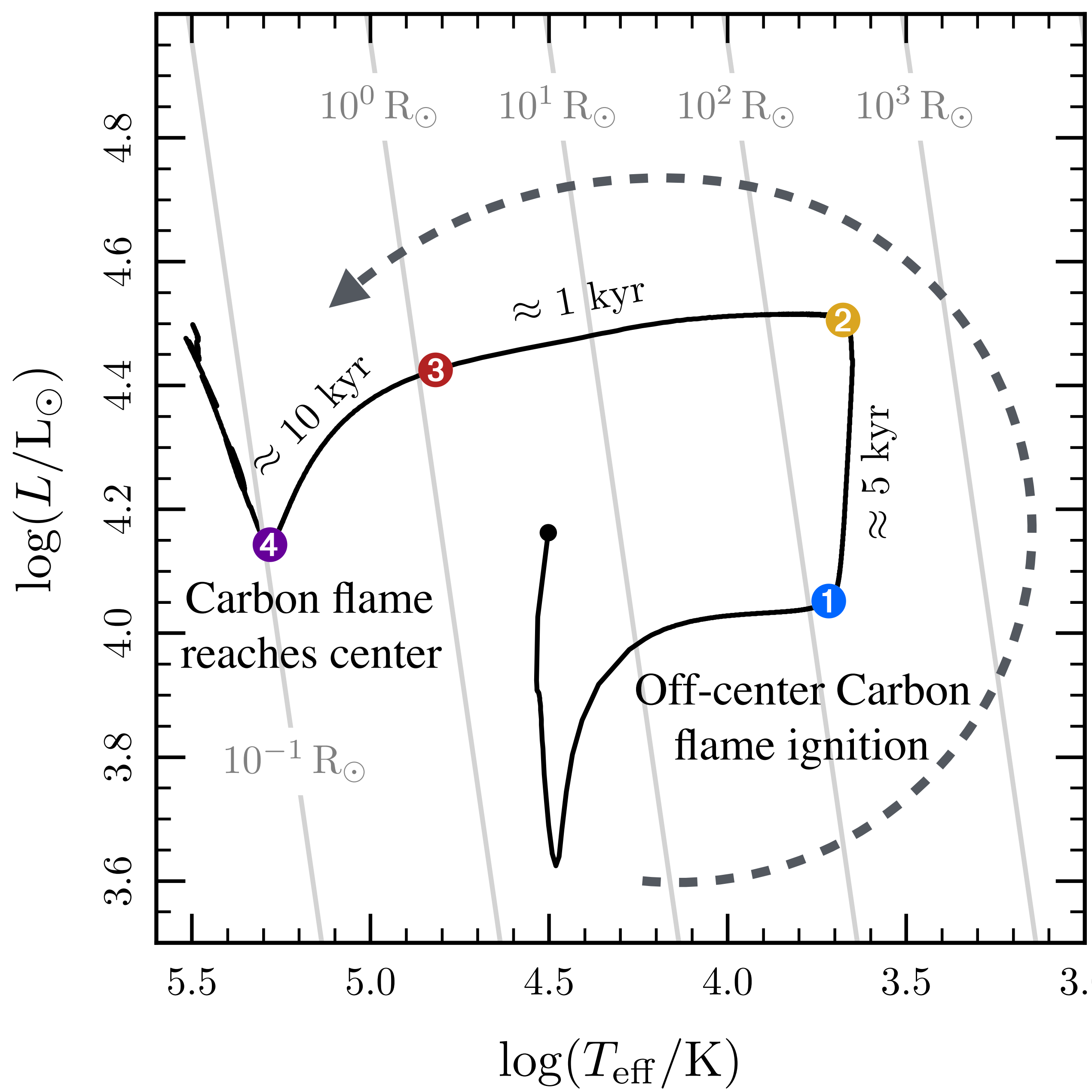
"Luminous giant" phase:

Envelope $(r_{env} \sim 100 R_\odot, T \sim 4000-5000\ \mathrm{K})$ radiates away merger energy at Eddington luminosity $(L \sim 10^{4.5} L_\odot)$ for ~10 kyr as Carbon flame travels inward

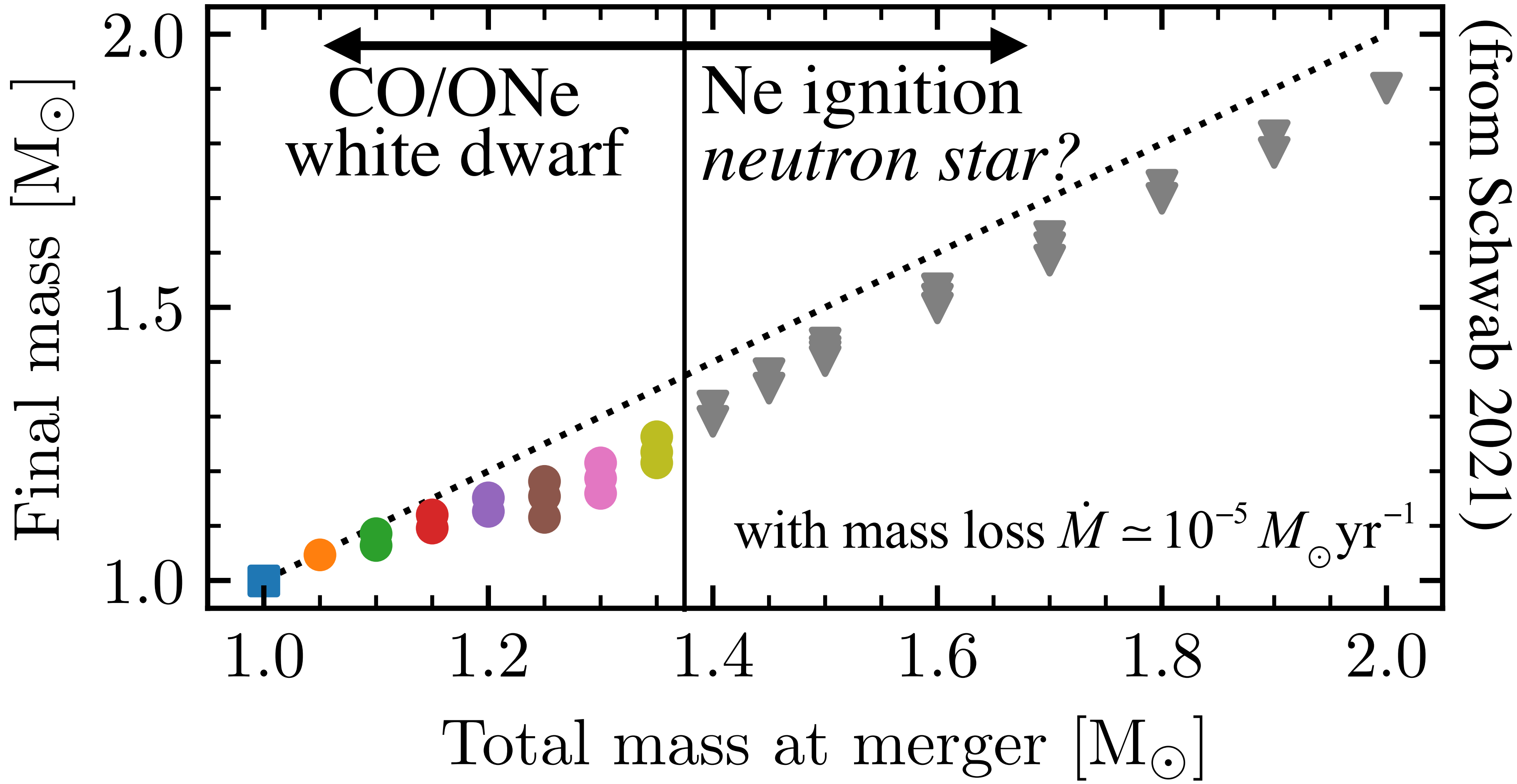
- *O* (10) sources expected in Milky Way and M31
- If dust obscured, bright infrared — sources for JWST?
- R Coronae Borealis stars? *(e.g., Webbink 1984, Clayton 2012)*
- J005311 — a possible candidate? *Gvaramadze+2019*

from Schwab+2016



After thermal phase

(noting *uncertain* envelope wind mass loss)



Highly magnetic and rapidly rotating remnant?

White dwarf remnant

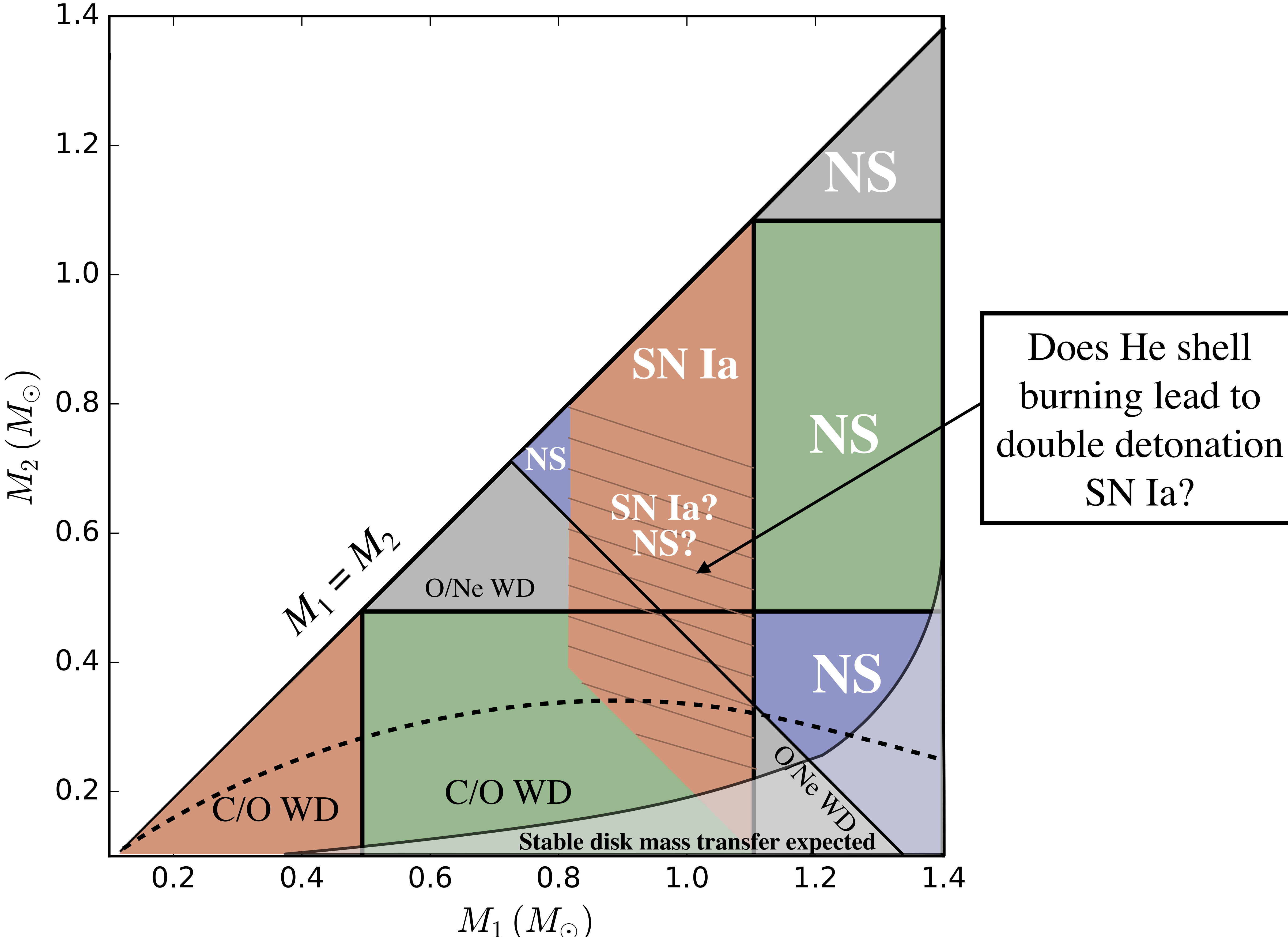
- e.g., Ferrario+1997, Külebi+2010, Hollands+2020, Caiazzo+2021

Neutron star/ (milli)second pulsar/magnetar?

- e.g., King+2001, Levan+2006, Schwab 2021, Kremer+2021
- Evidence in globular clusters?

Final outcomes for different merger masses

(adapted from Shen 2015; see also Dan+2014, Marsh+2004)

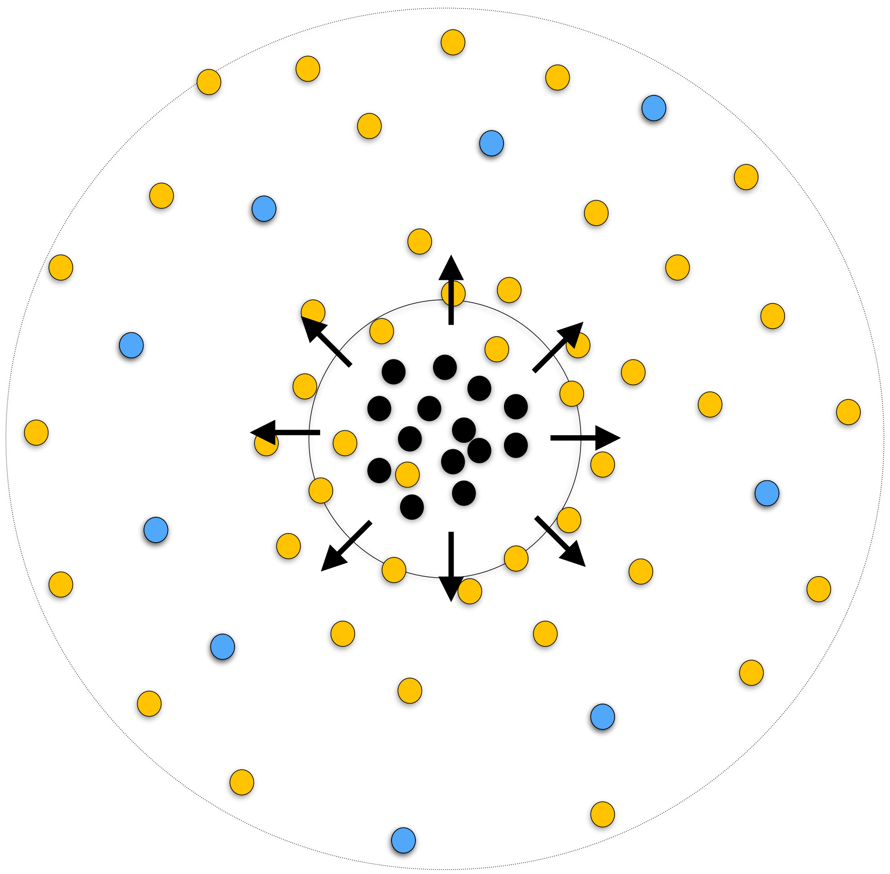


White Dwarf Mergers in Globular Clusters

Typical Globular Cluster:

- Main sequence stars ($M \approx 0.1 - 150\, M_\odot$; $N \approx 10^6$)
- Black holes ($M \approx 30\, M_\odot$; $N \approx 1000$)
- White dwarfs ($M \approx 0.5 - 1.4\, M_\odot$; $N > 10^4$)

Black holes *dynamically heat* host cluster through binary burning



Motivated by observations of XRBs, pulsars, CVs, white dwarfs in clusters *(e.g., Clark 1975, Grindlay+1995, Freire 2012, Richer+1995, Harris+1996)* and N-body modeling *(e.g., Mackey+2008, Breen & Heggie 2013, Morscher+2015, Wang+2016, Arca Sedda+2018, Askar+2018, Ye+2019, Kremer+2020)*

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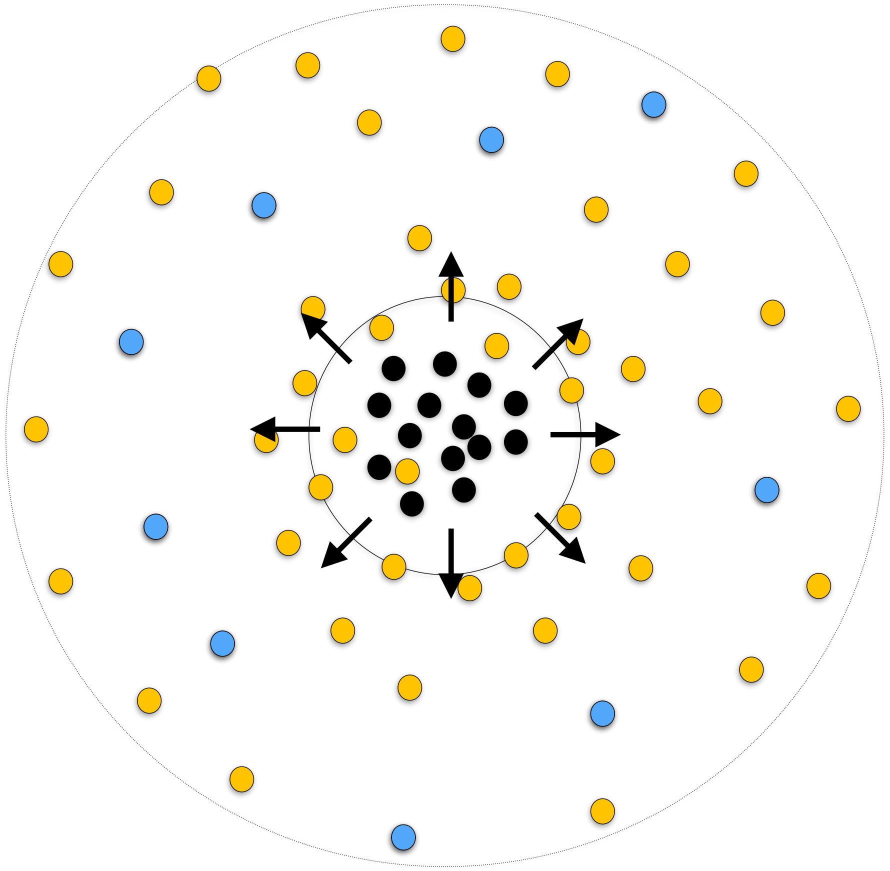

Talk to me later about:

- **Binary black hole mergers** *(LIGO sources)*
- **Stellar tidal disruption events** *(Rubin sources?)*

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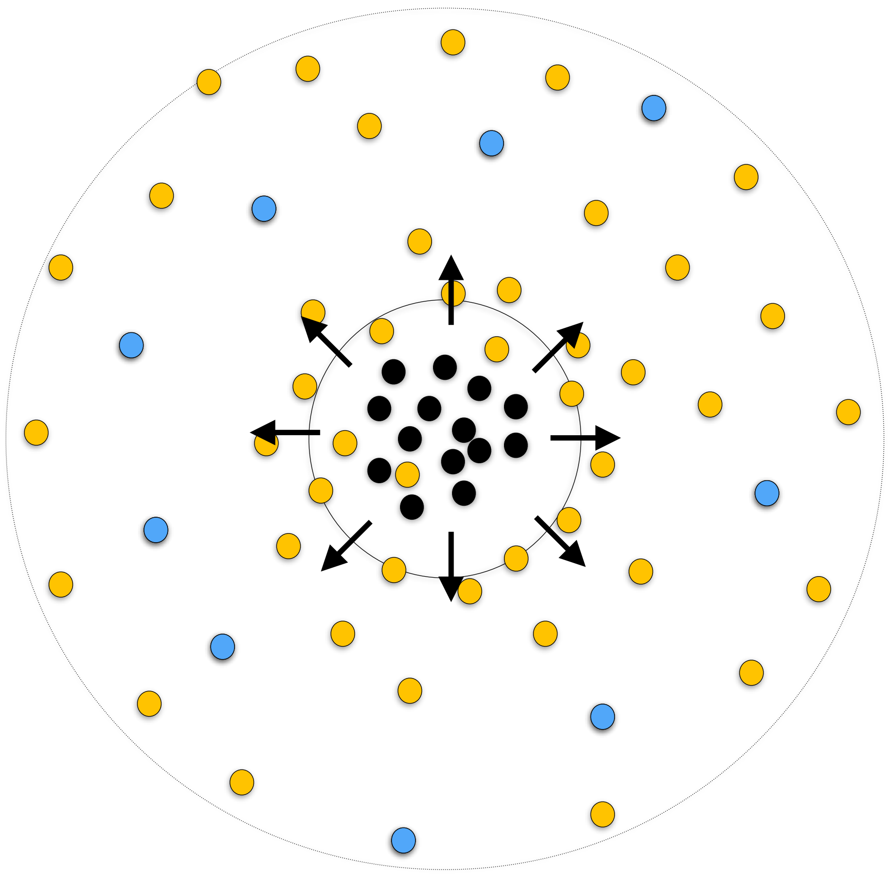
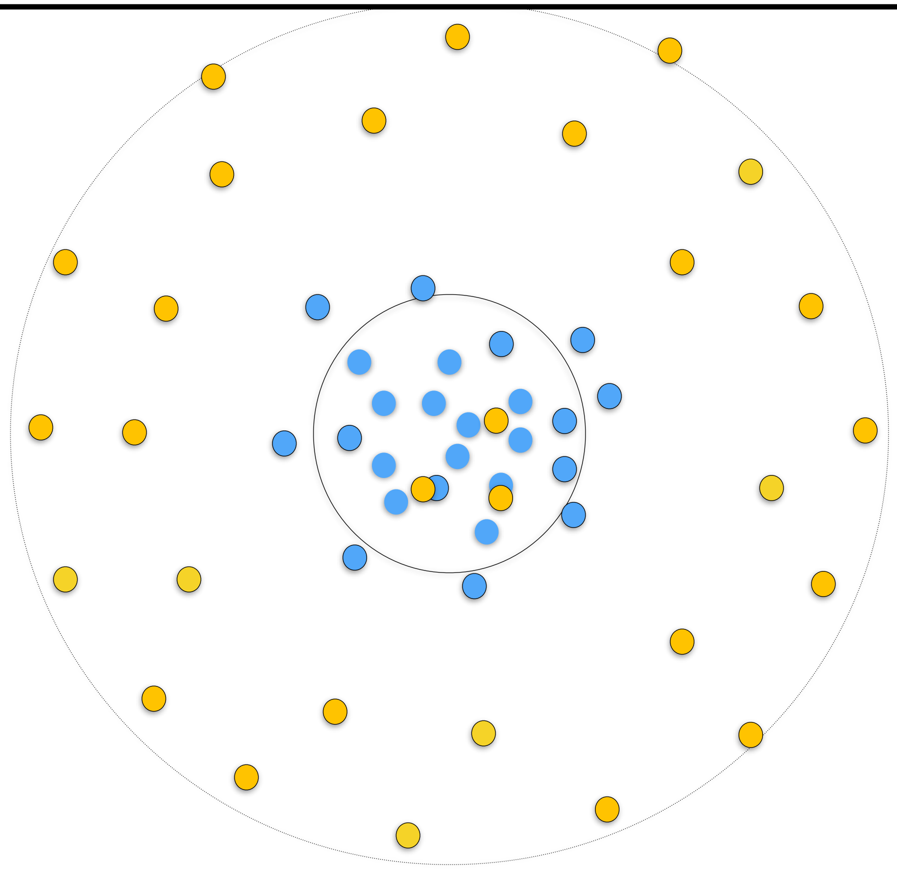


***Core-collapsed* Globular Cluster:**

- All black holes have been ejected
- Lower mass objects sink to center and cluster core collapses
- See Vitrol & Mamon 2021, Vitrol+2022 for constraints on central WD population in *NGC 6397*

In Milky Way ~20% of clusters have undergone core collapse



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Typical core-collapsed globular cluster:

$$n_{\mathrm{WD}} \approx 10^6\,\mathrm{pc}^{-3}$$

- Dozens of massive WD binaries
- Roughly 10 WD+WD mergers per Gyr
- O (1) resolvable LISA source per cluster

e.g., Larson+1984, Sigurdsson & Phinney 1995, Kremer+2021, Vitrol, Kremer+2022

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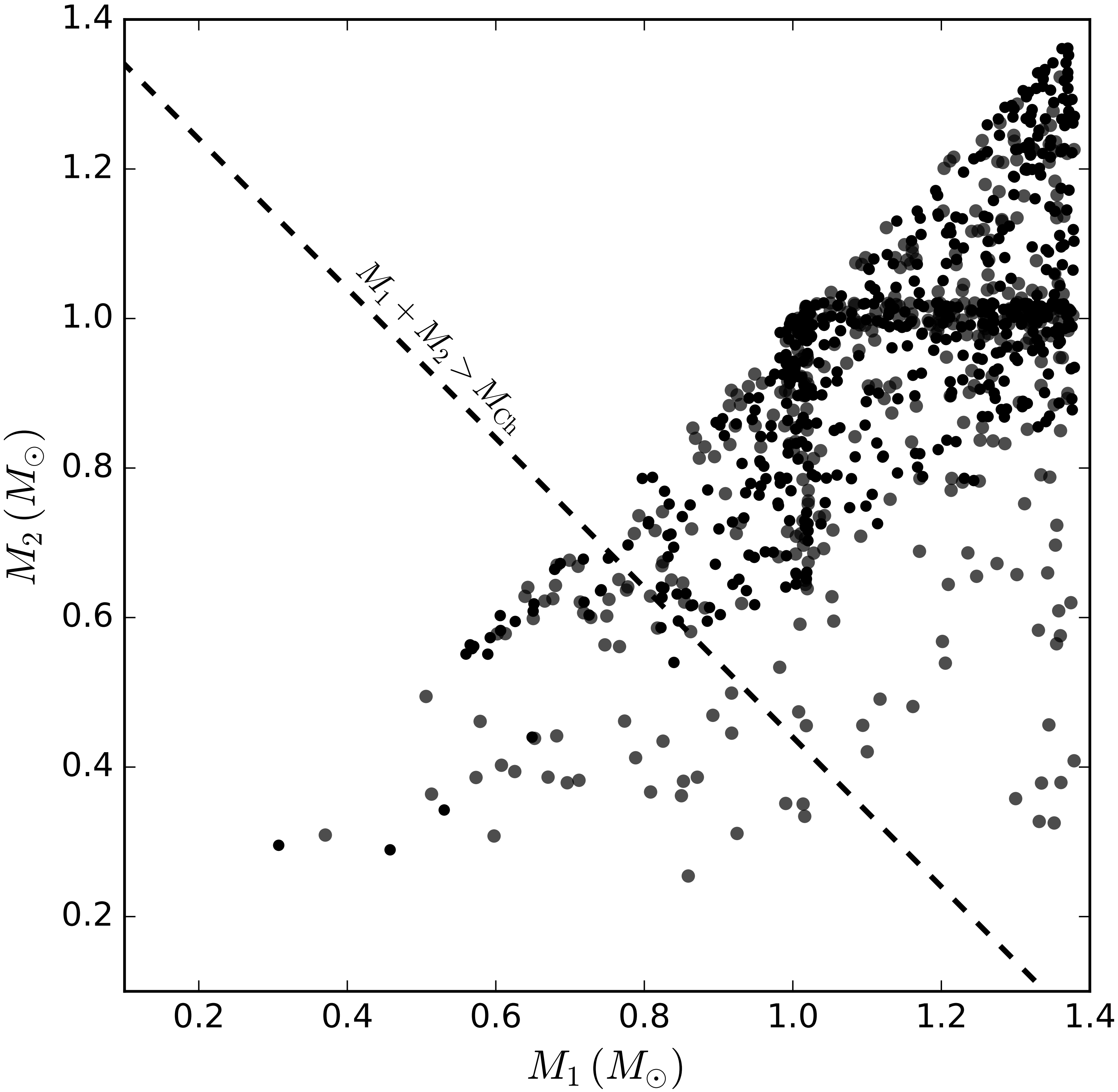
Merger outcomes from cluster simulations

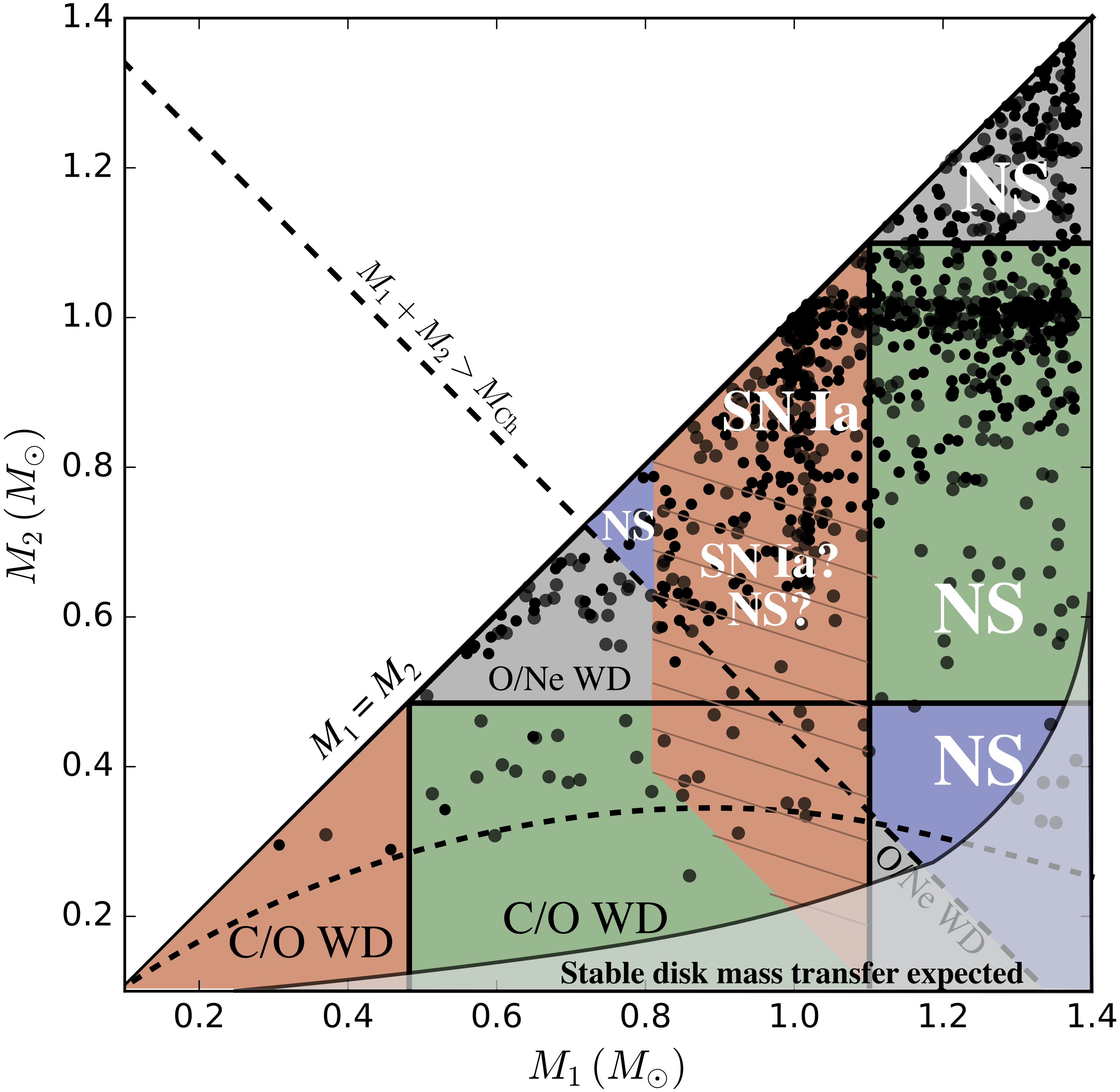
Kremer+2021



- **~90% of mergers have $M_{\rm tot} > M_{\rm Ch}$**

Merger outcomes from cluster simulations

Kremer+2021



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- **> 60% likely collapse to neutron star**

Merger outcomes from cluster simulations

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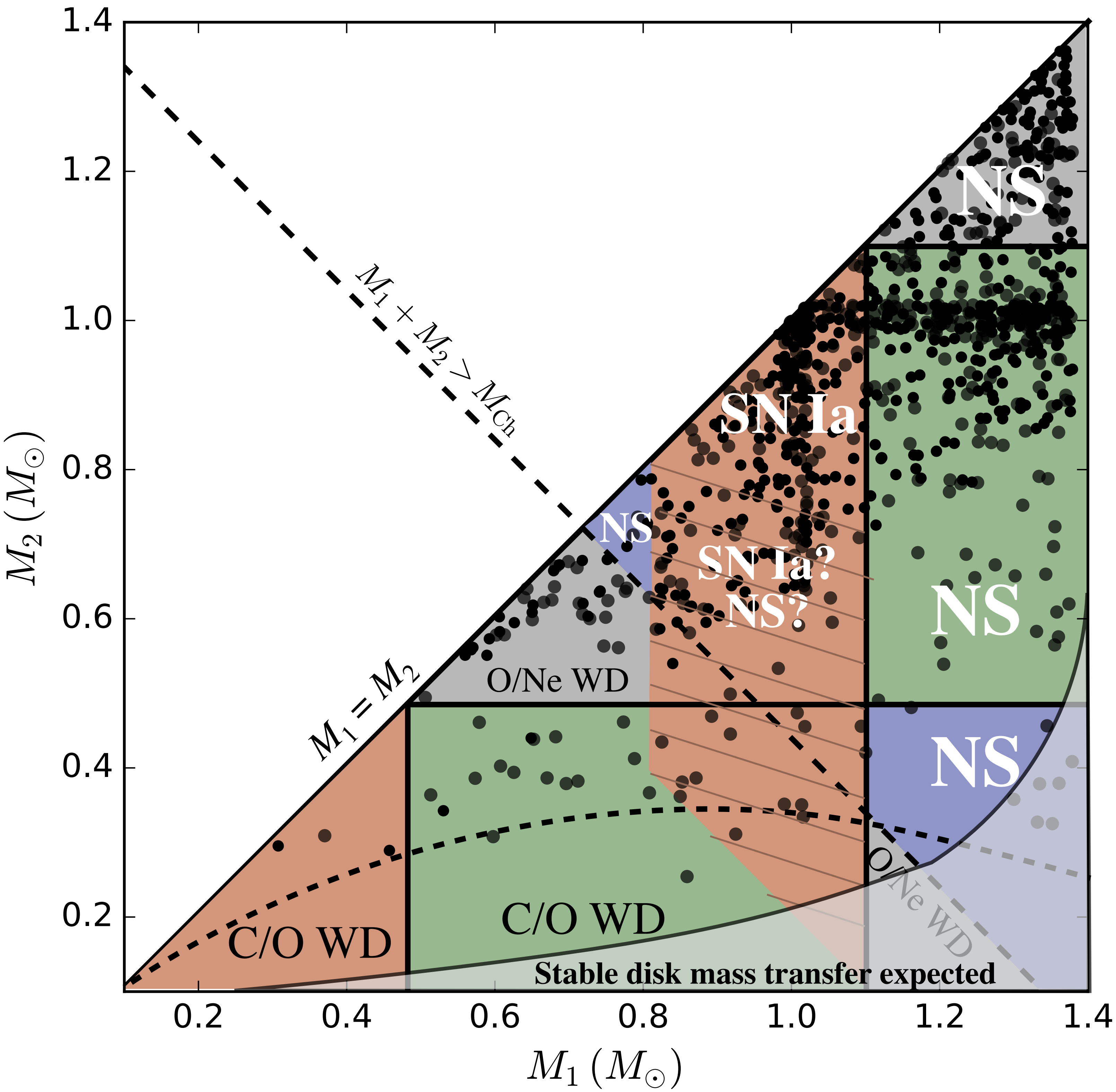


- **~90% of mergers have $M_{tot} > M_{Ch}$**
- **> 60% likely collapse to neutron star**

Type Ia SNe?

- Rate of up to ~50 $Gpc^{-3}\ yr^{-1}$ in local universe (<1% of SN Ia rate)

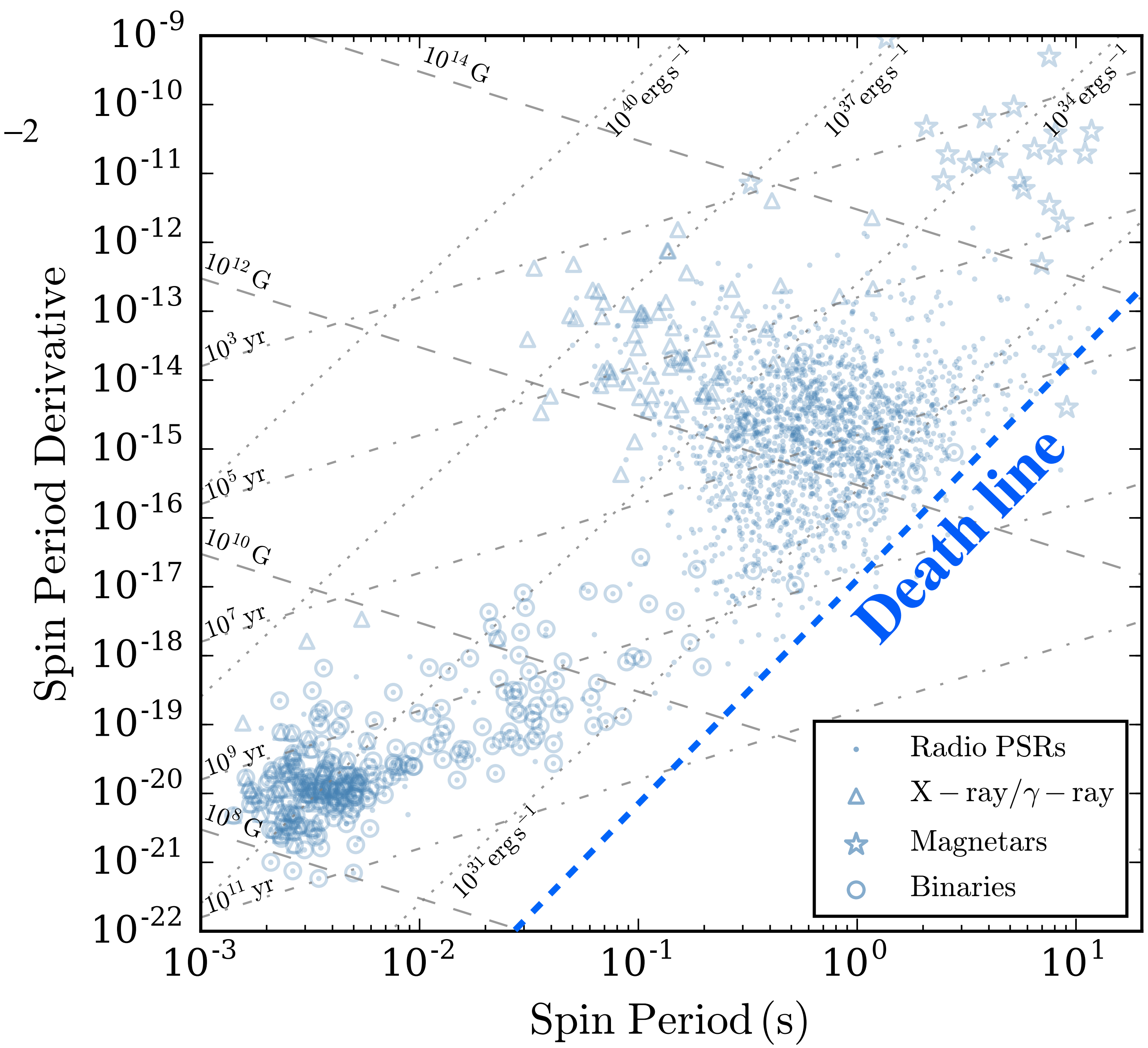
Observation of young NS in old GC would be clear evidence for this process

Detecting neutron stars as *pulsars*

- Pulsars spin down over time due to magnetic dipole radiation
- Unless recycled through accretion, pulsars eventually fall below "death line" and become undetectable

Characteristic age of a pulsar:

$$\tau_{\text{spin}} \approx \frac{P}{2\dot{P}} \sim 10^8 \text{ yr} \left(\frac{P}{100 \text{ ms}}\right)^2 \left(\frac{B}{10^{11}\text{G}}\right)^{-2}$$



In old (>10 Gyr) globular clusters, CCSN pulsars are now *undetectable*

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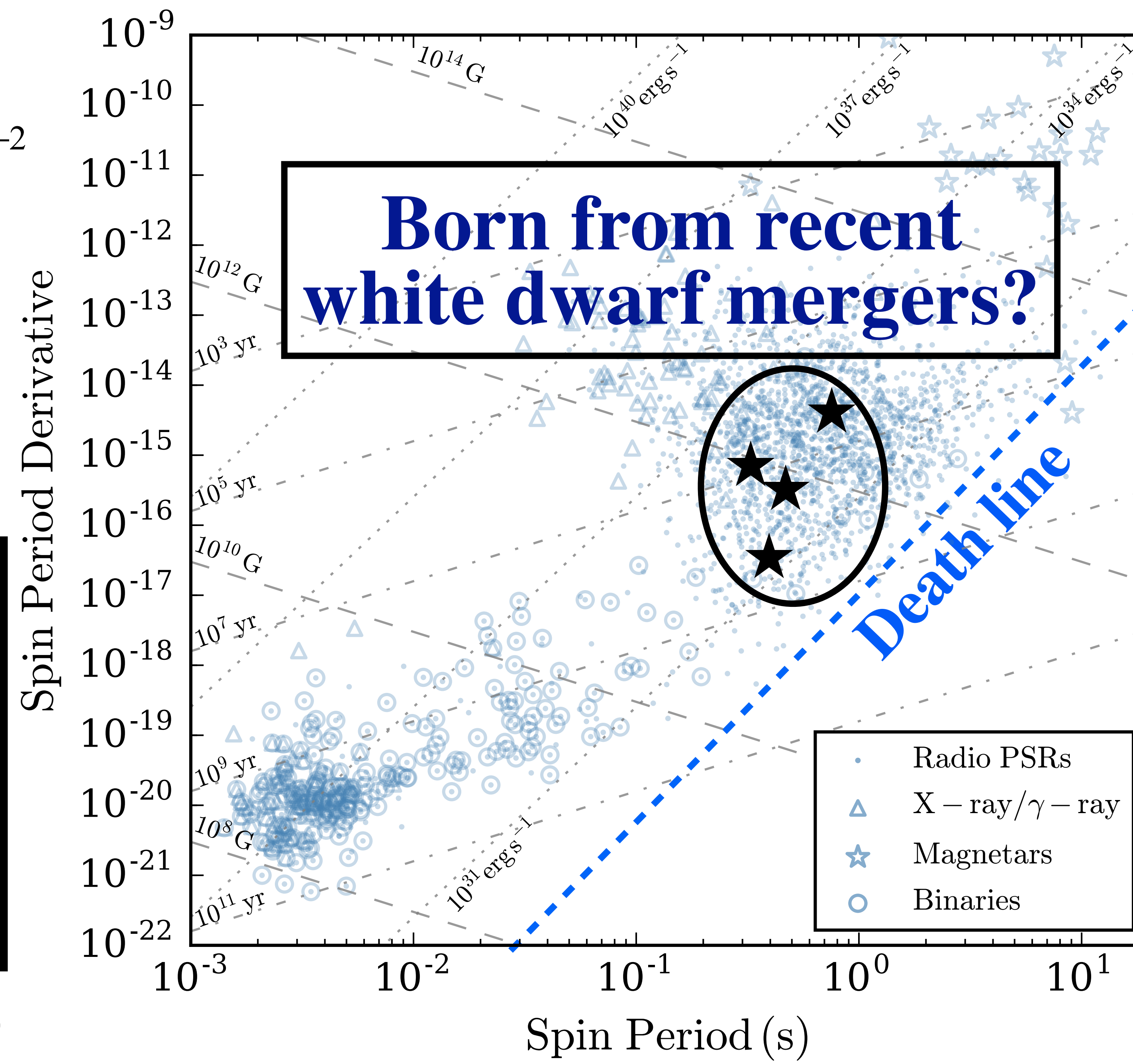
Four *young* pulsars observed in Milky Way globular clusters

	P (s)	$\dot{P}$ (s s^{-1})	B (G)	age (yr)
B1718-19	1.004	1.6×10^{-15}	1.3×10^{12}	9.8×10^{6}
J1745-20A	0.289	4.0×10^{-16}	3.4×10^{11}	1.1×10^{7}
J1820-30B	0.379	3.0×10^{-17}	1.1×10^{11}	2.0×10^{8}
J1823-3021C	0.406	2.2×10^{-16}	3.0×10^{11}	2.9×10^{7}

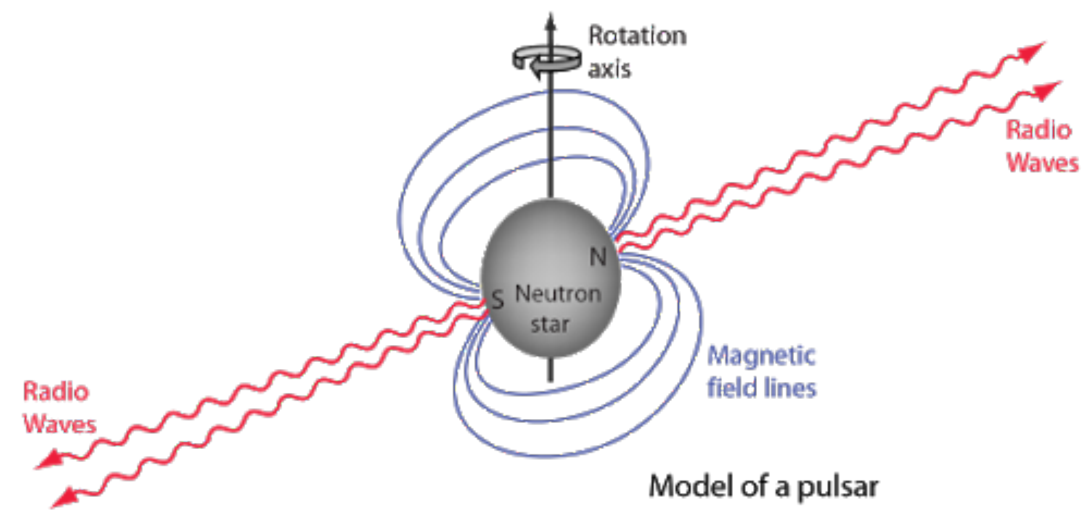
(e.g., Boyles+2011, Tauris+2013)



Neutron Stars: Sources of Fast Radio Bursts?

Proposed neutron star models:

- FRB powered by magnetic activity/rotation power
- Isolated? (e.g., pulsars, magnetars)
- Interacting? (e.g., accretion from binary companion)
- Merging NSs (e.g., similar to short GRBs)



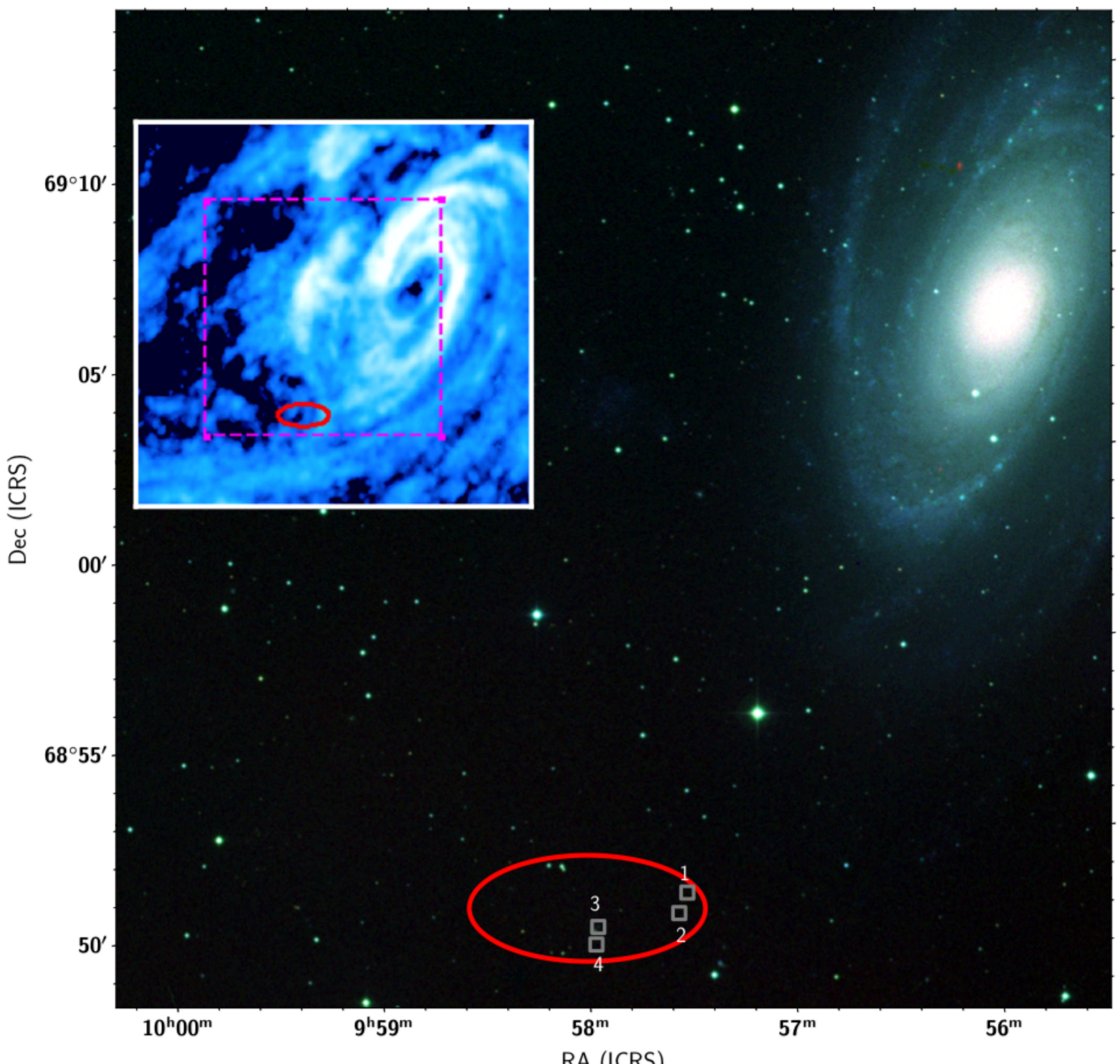
Recently…

FRB detected in Milky Way in association with a magnetar with known supernova remnant *(CHIME/FRB Collaboration+2020, Bochenek+2020)*

→ Magnetar models can explain at least some FRBs

A Repeating FRB in a Globular Cluster in M81

Bhardwaj et al. 2021 — Initial FRB detection
Kirsten et al. 2021 — Localization to a cluster



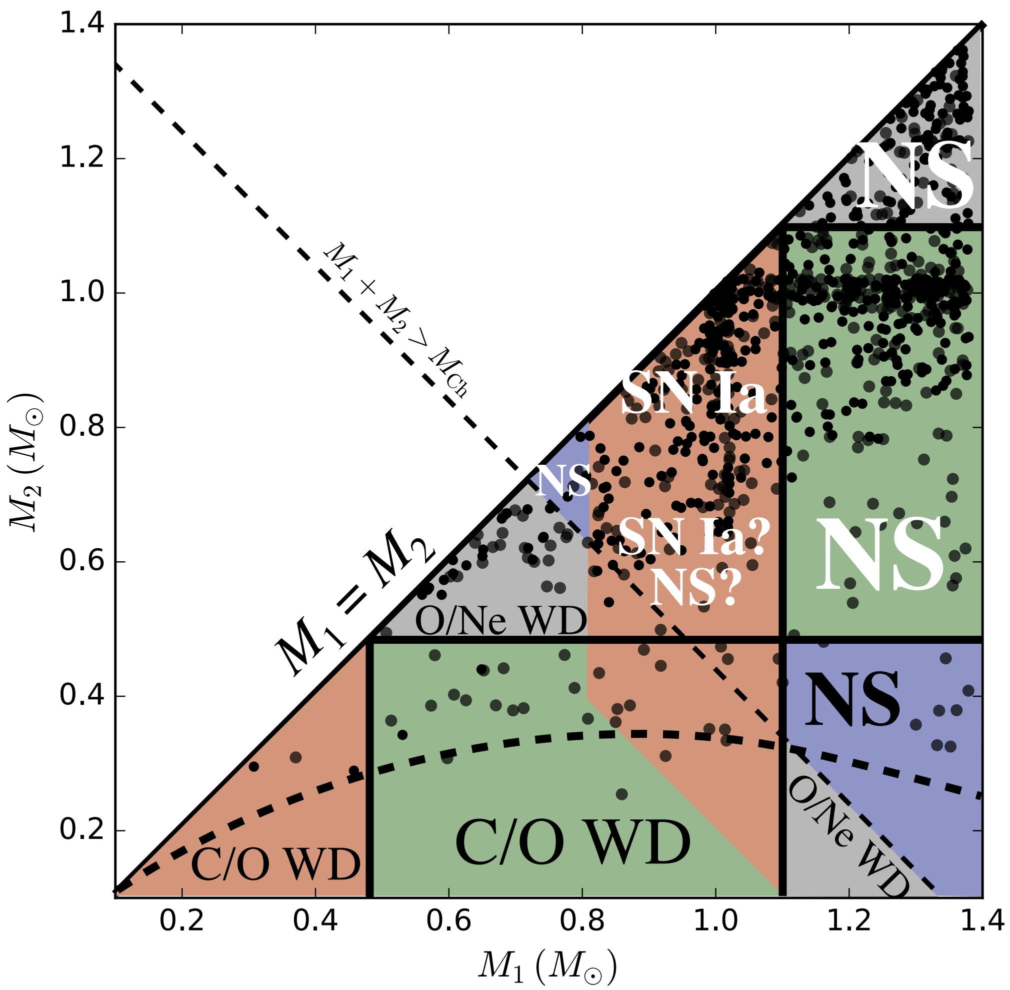
Digital Sky Survey RGB image of region near M81 from Bhardwaj+2021

- 7 bursts over ~100 hr on-source time
- Peak fluence ~ 1 Jy ms —> peak (radio) luminosity ~ 10^{37} erg/s
- Distance ~ 3.6 Mpc (closest extragalactic FRB known)

- CCSN magnetar *cannot* explain this source!

M81 FRB powered by magnetar from white dwarf merger

Kremer, Piro & Li 2021; see also Lu, Beniamini & Kumar 2022



Active FRB lifetime of ~10^6 yr is consistent with M81 FRB detection for cluster WD merger rate of ~10 Gpc^{-3} yr^{-1}

Spin-down timescale:

$$\tau_{\rm spin} \approx \frac{P}{2\dot{P}} \sim 10^6 \text{ yr} \left(\frac{P}{10 \text{ ms}}\right)^2 \left(\frac{B}{10^{11}\text{G}}\right)^{-2}$$

Magnetic activity timescale:

$$\tau_{\rm mag} \approx 10^6 \text{ yr} \left(\frac{B}{3\times 10^{14}\text{G}}\right)^{-1.2} \left(\frac{L}{1\text{km}}\right)^{1.6}$$

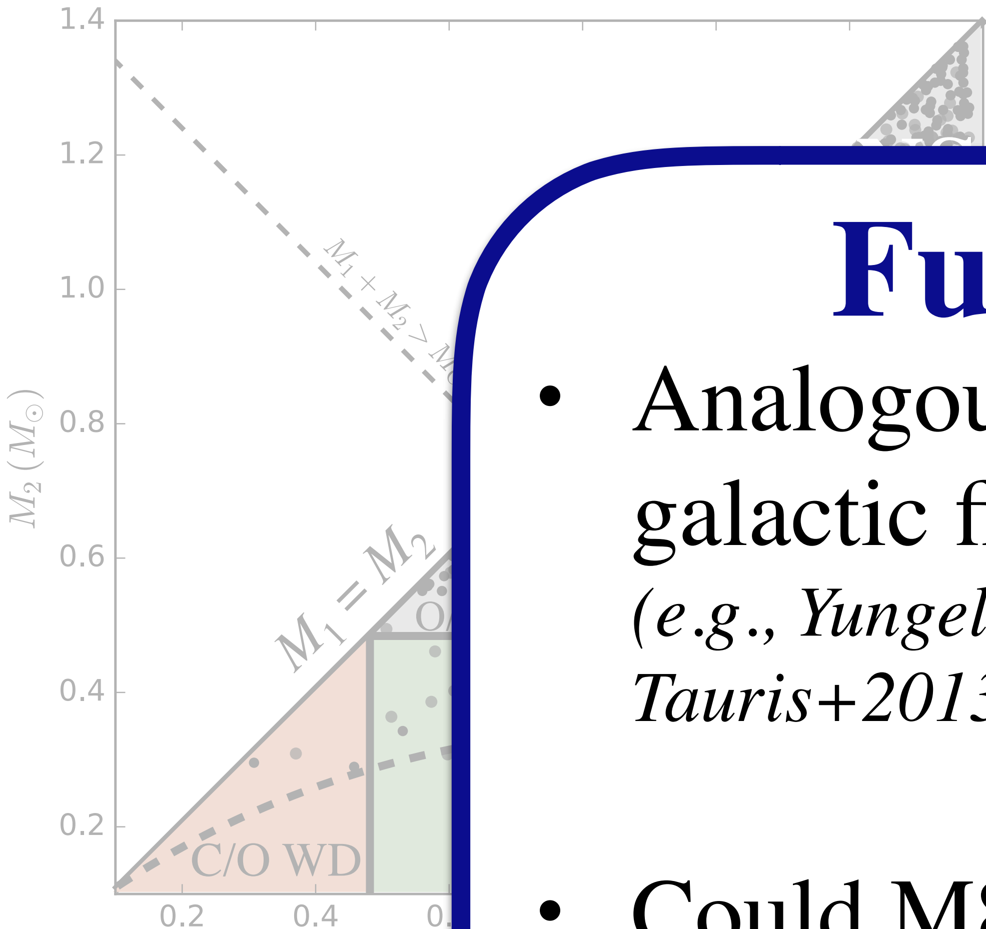
Both plausibly consistent with energetics for radio efficiency, $f_{\rm r} << 1$

Observed time-averaged (isotropic equiv) luminosity:

$$\left\langle \dot{E} \right\rangle \approx 10^{29} f_{\rm r}^{-1} \text{ erg s}^{-1} \quad \text{(from CHIME; Bhardwaj+2021)}$$

M81 FRB powered by magnetar from white dwarf merger

Kremer, Piro & Li 2021; see also Lu, Beniamini & Kumar 2022



Active FRB lifetime of ~10^6 yr is consistent

cluster WD

yr $^{-1}$

Future prospects:

- Analogous massive WD mergers in galactic fields — at similar/higher rate? *(e.g., Yungelson & Livio 1998, Fryer+1999, Tauris+2013, Kwiatkowski 2015)*
- Could M81 FRB-like events be common features of old stellar populations?
- **Stay tuned!** (CHIME, FAST, SKA, …)

$\frac{B}{10^{11}\,\mathrm{G}}\Big)^{-2}$

$\frac{L}{\mathrm{km}}\Big)^{1.6}$

Both

Obser

$y, f_r << 1$

$\langle E \rangle \approx 10^{29} f_r^{-1}$ erg s^{-1} (from CHIME; Bhardwaj+2021)

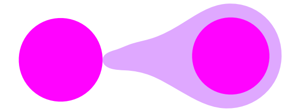
White Dwarf Binaries as Multimessenger Sources

Binary inspiral

Optical
(e.g., Burdge+2020)

Gravitational waves (LISA)
(e.g., Amaro-Seoane+2020)

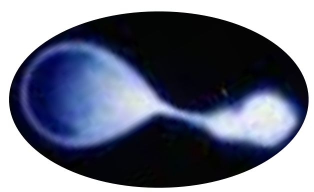
Roche lobe overflow



stable?

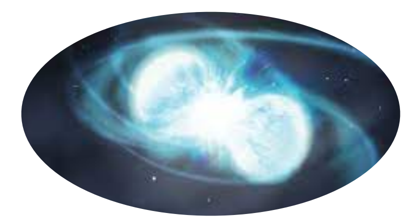
AM CVn

X-ray/UV/ optical
(e.g., Smak 1967)
LISA



unstable?

Merger



detonation?

SN Ia

(e.g., Maoz+2014)

no detonation?

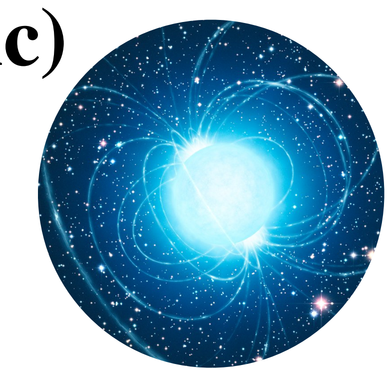
Optical/Infrared
(e.g., Gvaramadze+2019?)

Viscous disk → "Luminous giant"

sub-Chandra?

Massive (magnetic) white dwarf

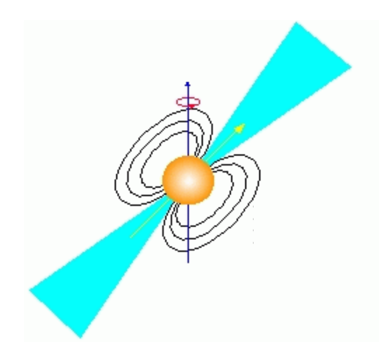
e.g., optical
(e.g., Caiazzo+2021)



super-Chandra?

Neutron star

Radio pulsars?
(e.g., Boyles+2011)
Fast radio bursts?
(e.g., Bhardwaj+2021)



Questions?

How to form a young neutron star in a cluster?

1 FRB in M81 implies volumetric density $n_{\mathrm{FRB}} \sim 5\times10^{6}\ \mathrm{Gpc}^{-3}$

Active lifetime required, $\tau \approx 5\times10^{6} / R_{\mathrm{src}}$

We constrain FRB source formation rates from large suite of globular cluster N-body models; Kremer+2020, 2021

Event type	Total # in models	Rate per CC GC $[\mathrm{yr}^{-1}]$	Volumetric rate $[\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}]$	Active lifetime required (τ) $[\times(f_v\zeta)^{-1}]$
Super-Chandrasekhar WD+WD mergers	283	6×10^{-9}	4	10^{6} yr
(estimate including tidal capture)	-	7×10^{-8}	45	10^{5} yr
WD+NS mergers	59	10^{-9}	0.8	6×10^{6} yr
(estimate including tidal capture)	-	10^{-8}	6	8×10^{5} yr
NS+NS mergers	6	10^{-10}	0.08	6×10^{7} yr
AIC from binary RLO	21	5×10^{-10}	0.3	2×10^{7} yr
WD+MS collisions ($M_{\mathrm{WD}} > 1.2\,M_{\odot}$)	1098	2×10^{-8}	15	3×10^{5} yr
NS+MS collisions	301	7×10^{-9}	4	10^{6} yr
Inferred rate for M81 FRB	-	-	$\approx 5\times10^{6}/\tau$	-

See Kremer, Piro & Li 2021, ApJL (arXiv:2107.03394)

Burst Energetics

Total burst fluence 6.6 Jy ms (Bhardwaj+2021) over ~100 hr on-source time gives time-averaged (isotropic equiv) luminosity:

$$\left\langle \dot{E} \right\rangle \approx 10^{29} f_{\mathrm{r}}^{-1} \ \mathrm{erg\ s^{-1}}$$

Magnetically powered:

(e.g., Popov & Postnov 2010, Lyubarsky 2014, Beloborodov 2017, Wang+2018, Metzger+2017, 2019)

$$E_{\mathrm{mag}} \approx \frac{1}{6}(B^2 R^3)$$

$$\tau_{\mathrm{mag}} \approx 2\times10^5 \left(\frac{B}{10^{14} G}\right)^{-1.2} \left(\frac{L}{1\mathrm{km}}\right)^{1.6} \mathrm{yr}$$

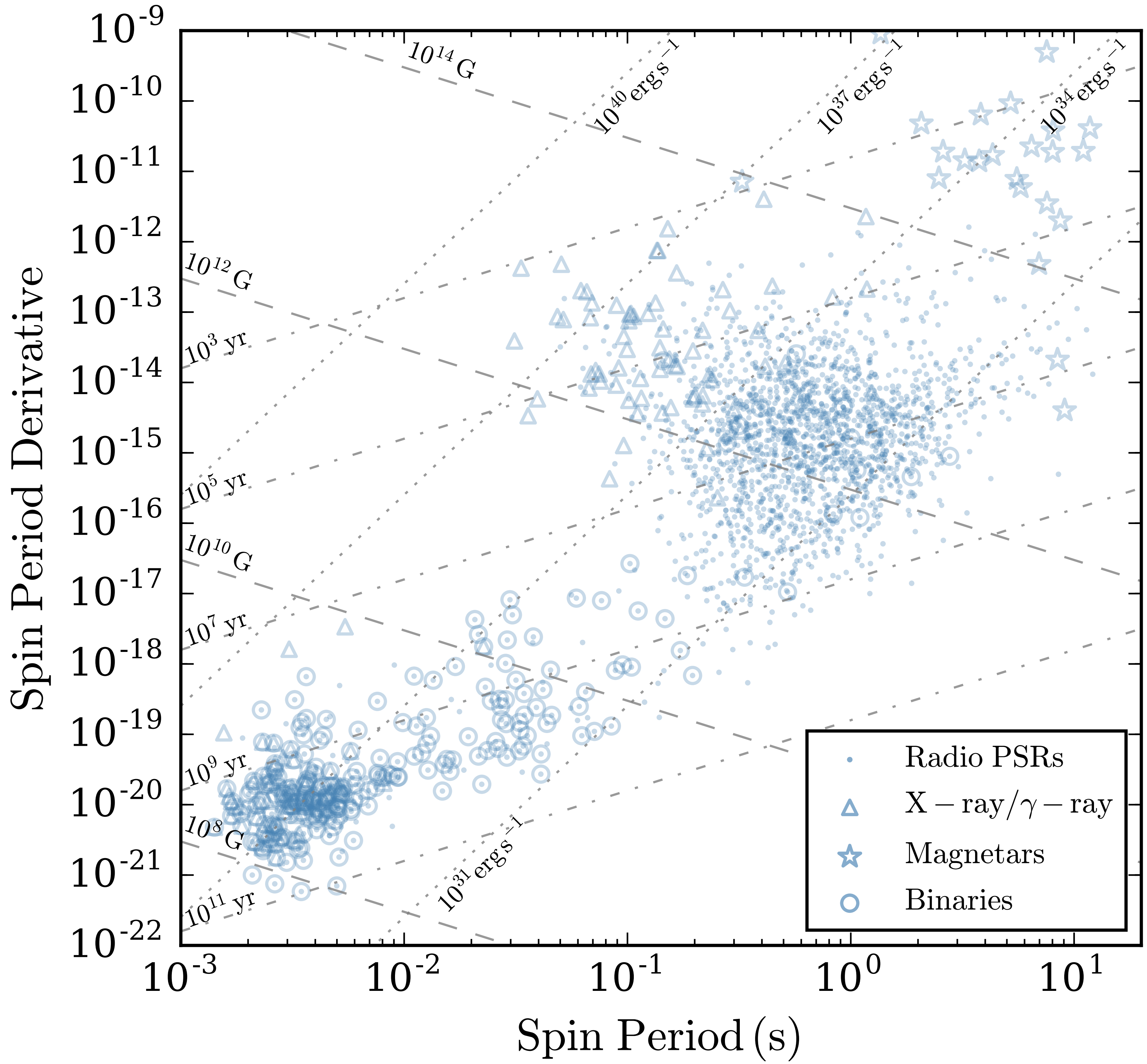
Spin down powered:

(e.g., Cordes & Wasserman 2016, Connor+2016, Lyutikov+2016)

$$E_{\mathrm{rot}} \approx 2\pi^2 I \ P^{-2}$$

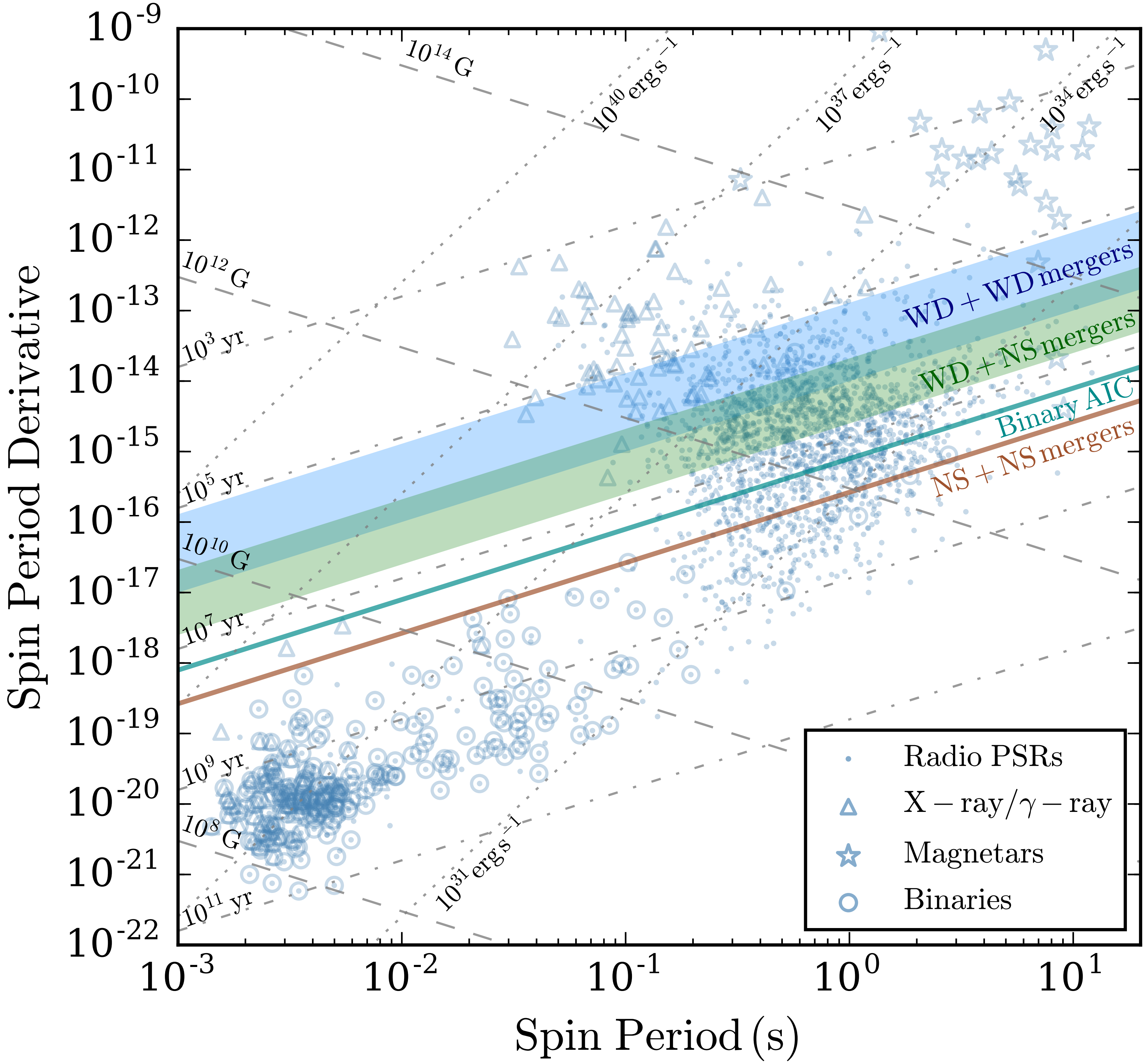
$$\tau_{\mathrm{rot}} \approx \frac{P}{\dot{P}} \approx 5\times10^5 \left(\frac{P}{10\mathrm{ms}}\right)^2 \left(\frac{B}{10^{11}\mathrm{G}}\right)^{-2} \mathrm{yr}$$

Inferring Neutron Star Properties



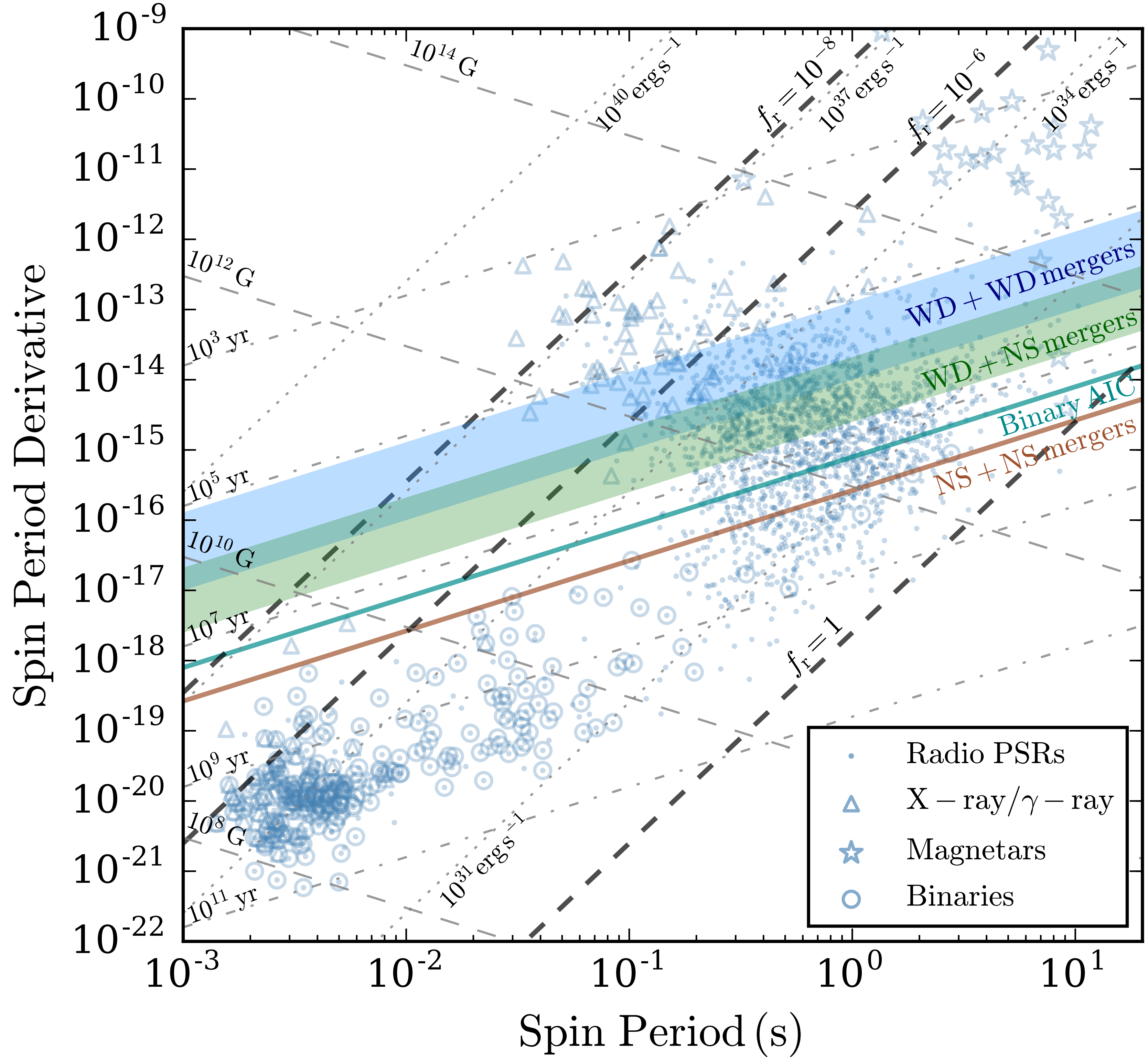
See Kremer, Piro & Li 2021, ApJL (arXiv:2107.03394)

Inferring Neutron Star Properties



See Kremer, Piro & Li 2021, ApJL (arXiv:2107.03394)

Inferring Neutron Star Properties

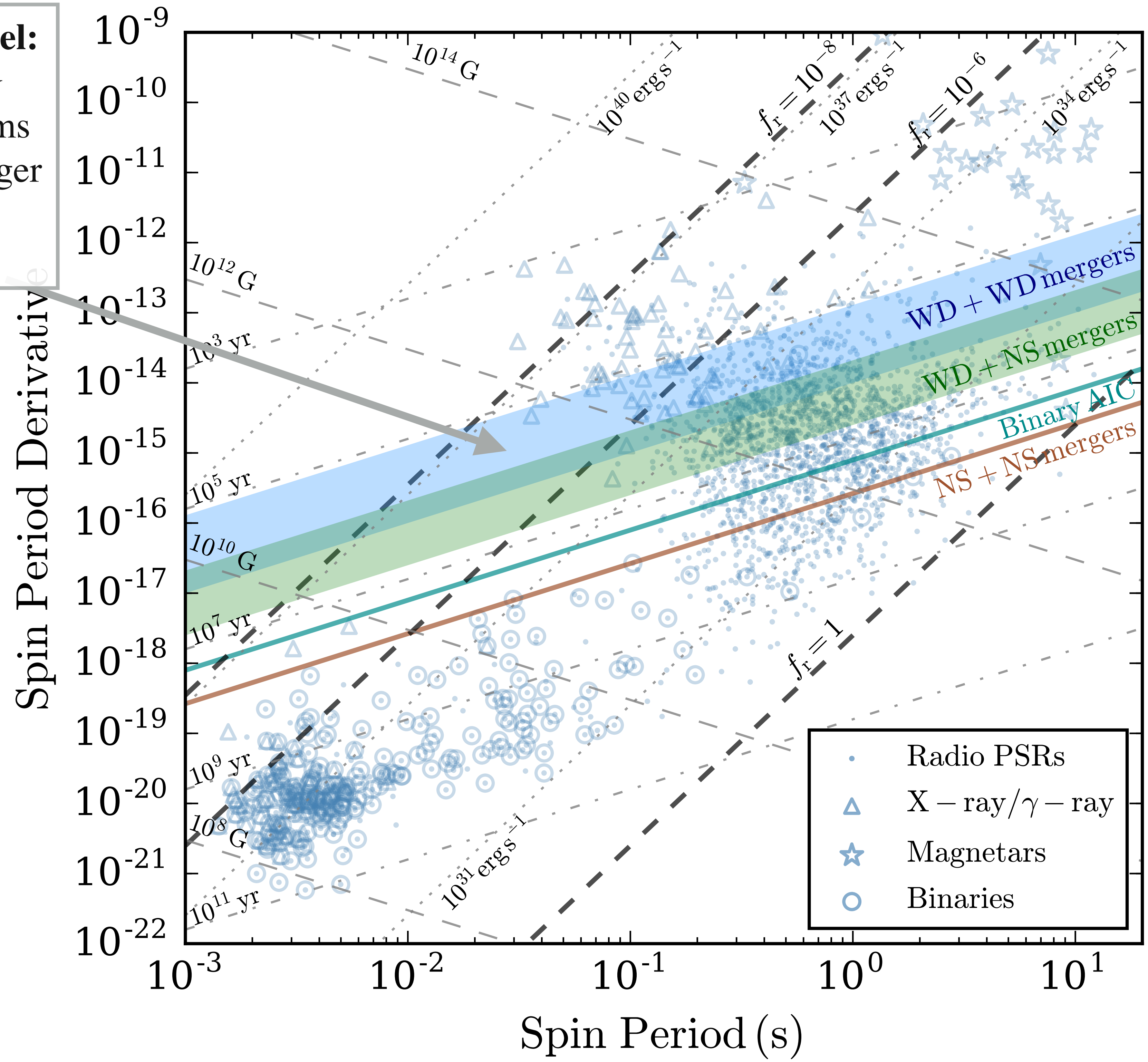


See Kremer, Piro & Li 2021, ApJL (arXiv:2107.03394)

Inferring Neutron Star Properties

Spin-down powered model:
- B-fields of ~10¹¹ -10¹² G
- Spin periods of ~10-100ms
- Consistent with WD merger simulations

(e.g., Schwab 2016, 2021)



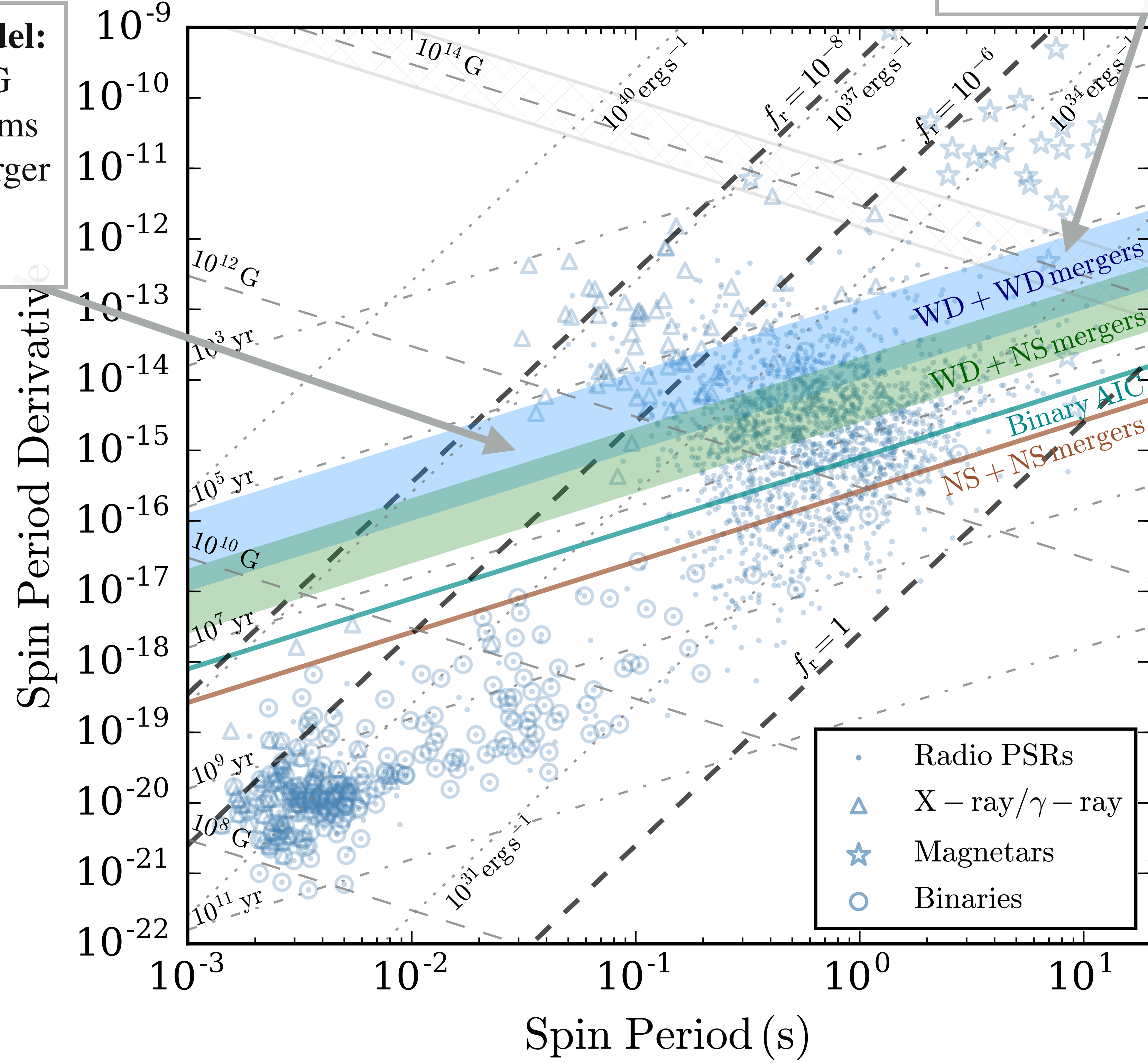
See Kremer, Piro & Li 2021, ApJL (arXiv:2107.03394)

Inferring Neutron Star Properties

Magnetically-powered model:
- Requires B~10^{14} G and $f_r > 10^{-4}$
- Requires lifetime > observed lifetimes for Galactic magnetars

Spin-down powered model:
- B-fields of ~10^{11} -10^{12} G
- Spin periods of ~10-100ms
- Consistent with WD merger simulations

(e.g., Schwab 2016, 2021)



See Kremer, Piro & Li 2021, ApJL (arXiv:2107.03394)

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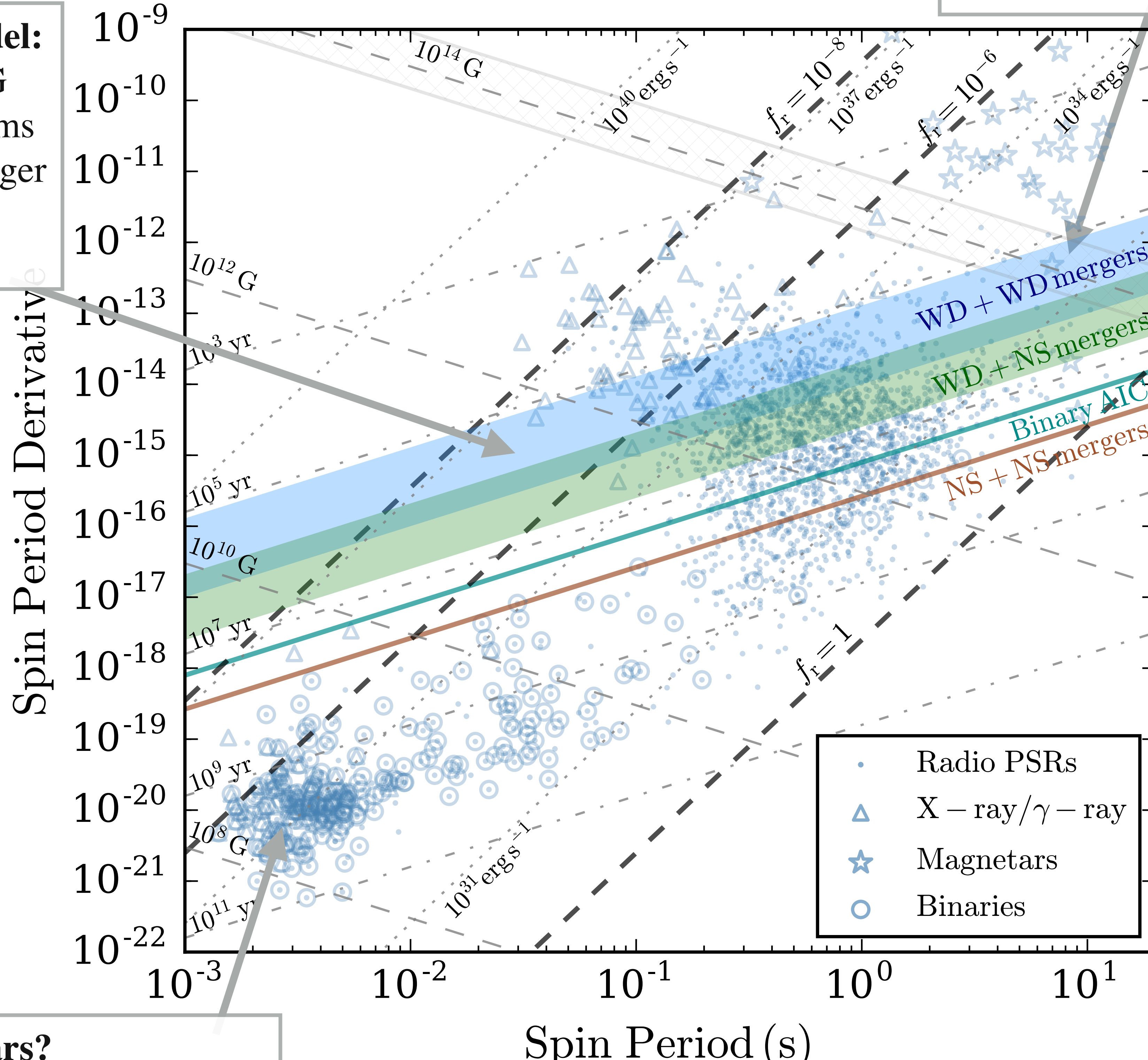

Millisecond pulsars?
- Viable only for efficient radio emission and small duty cycle

See Kremer, Piro & Li 2021, ApJL (arXiv:2107.03394)

Key take aways…

See Kremer, Piro & Li 2021, ApJL (arXiv:2107.03394)

- Core-collapsed globular cluster is most likely host — future observations may confirm this
- Young neutron stars are formed at rate of ~50 $\mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$ in clusters local universe, likely sufficient to explain M81 FRB
- Magnetically-powered scenario is viable for radio emission efficiency $f_r > 10^{-4}$ and lifetimes longer than empirical lifetimes for Galactic magnetars
- Also viable are spin-down powered NSs with spin periods ~10ms and $B \sim 10^{11}$ G *(consistent with those expected from WD mergers)*
- Millisecond pulsars and/or X-ray binaries are viable if duty cycles for FRB emission is not too high
- X-ray binary may also be viable (e.g., Katz 2017, Sridhar+2021, Deng+2021)